

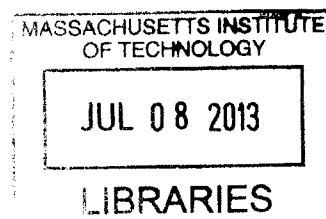
Communication Options for Protection and Control Device in Smart Grid Applications

ARCHIVES

by

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B.S. Electrical and Computer Engineering
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Computer Science

Abstract

Increasing use of electricity, interest in renewable energy sources, and need for a more reliable power grid system are some of the many drivers for the concept of the Smart Grid technology. In order to achieve these goals, one of the critical elements is communication between systems or between the system and human beings. With the decreasing cost of various communication technologies, especially wireless devices and utilities, researchers are increasingly interested in implementing complex two-way communication infrastructures to enhance the quality of the grid. The protection and control relay at the distribution level is one of the key component in enhancing the efficiency, security and reliability of power grid. At present, it may be premature to apply wireless devices to power electronics and to distribution automation, especially for protection and control relays in the distribution level. While fiber technology is still very attractive for protection and control applications in general, wireless technology can bring improvements in user experience applications in the future. The ABB medium voltage group needs to overcome challenges that arise from conservative industry structure, increasing complexity and cost of the product, and needs for higher reliability and security. However, with collaborative efforts among different product groups, the medium voltage group will successfully develop next generation distribution feeder relay.

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1 Project Overview and Definition

1.1 Project Statement

The main function of a relay in electrical distribution is control of circuit breakers and protection of downstream circuits; its decision logic is based on the system inputs (e.g., fault current). However, with the evolution of telecommunications, the protection and control relay is now evolving into a device in which effective and secure communication capability is critical. Currently, many relay inputs and outputs travel along copper wires and fiber optics in analog form; series and Ethernet connections are also available as communication options for digital signals. With fast development of communication technology, there are many different available options in the space depending on the application and transmission distance. Currently, wired communication using copper wire is the most prevalent form of communication. With enhanced throughput, security and reliability fiber optics is another rising communication technology especially in a high voltage area. Wireless technologies are just entering into the power grid with the introduction of applications covering wide areas and requiring redundant communication. For the protection and control relay, there is no wireless option available for the utilities other than external implementations. However, wireless can provide benefits to the device regarding enhanced user experience. Different wired and wireless technologies and potential implementations will be discussed in a later chapter.

The goal of this project was to investigate communication requirements and technologies of next generation protection and control devices for Smart Grid applications. The primary focus is to understand external and internal communications requirements for the device and determine potential communication implementations. This thesis will start with a general overview of Smart Grid technology, analyze available wireless technologies and dive specifically into current communication methods for the protection and control relay. The following are the key objectives of this thesis:

- Analyze internal and external communications requirements and suggest potential communication implementations for relay applications
- Categorize and specify various wireless technologies that can be used for Smart Grid applications
- Investigate key features and characteristics of Smart Grid communication related to the protection and control relay
- Identify challenges to implement wireless communication technology in the protection and control relay for distribution automation

1.2 Project Background

1.2.1 ABB Back ground

ABB is a global leader in the area of power and automation technologies. ABB is headquartered in Switzerland with a strong market share worldwide, but its position in North America is not dominant. Its power products business is sub-divided into the High Voltage, Medium Voltage, and Transformers business units. Each sub organization is comprised of the global office for strategic decision-making and the regional offices responsible for execution and market specific strategies. The organization of both offices is matrix-structured for final production. The ABB Power Products Medium Voltage (PPMV) US head office is located in Lake Mary, FL, and oversees additional operations in Coral Springs, FL, Pinetops, NC, Florence, SC, and San Luis Potosi in Mexico.

The ABB Relion family of microprocessor-based protection and control relays has been developed using a platform strategy where core HW & SW components are shared across all global markets. The basic product is designed and developed in Finland, and the final customizations and market specific tests are done in the US. As a result of a more regionally focused strategy, future product platform development

will be based more strongly upon a distributed development model where regional R&D centers will be heavily involved in the development of products for the local market.

1.2.2 ABB US PPMV Business

Companies in the power industry, including ABB, are facing rapid market change and increasing competition mainly due to the Smart Grid implementation. This recent change in the industry forces the company to adapt quickly and to change its conservative attitude. In order to survive, the company has to react quickly and efficiently to meet market needs. ABB Power Product Medium Voltage (PPMV) group has recently started a crucial initiative to focus on products for specific markets, such as North America, in order to stay competitive and satisfy utilities. To achieve this strategic goal, however, overall change efforts and changes in management systems and cultural environments may be required. Organizational structure issues in integration and communication must be resolved in order to successfully hold and increase ABB PPMV's market share in North America.

The ABB medium voltage group has been facilitating the platform-base strategy where almost identical products were sold all around the world. This strategy encouraged the group to adopt a functional structure and the groups were further divided by the functional units depending on the product lines. As the group expanded its market to the US, the group structure evolved into a more complex matrix structure with multiple reporting and group hierarchies. With recent efforts to develop market-specific products and to move away from the platform-based strategy, the medium voltage group is in the process of moving toward the market-based structure where products are specifically built and developed for a regional market rather than using uniform platforms for global market.

Because the Finland office has served as the main research and design center for the product, there has not been a good new product R&D process in the US office. With the "By Region, For Region" initiative to develop products for the local market, the US office is trying to build up knowledge and processes

necessary to start visible product development activities within a few years. This project may be one of the early efforts to start this process successfully. The focus of the project is to develop a technology roadmap for future generation protection and control relays. One of the challenges is to identify and link resources necessary to develop the roadmap since the company structure is not yet prepared for a market based structure. In order to develop a competitive product for the market, it is important to have a system, team and process that can support R&D activities. Until today, the US offices mainly functioned in a maintenance role to resolve critical problems and issues with the product. Thus, the team is more familiar with problem solving and understanding the current situation rather than thinking creatively and innovatively. Furthermore, the US office is in the process of developing technical knowledge but not creating next generation products where the engineers are not yet ready for new R&D activities.

1.2.3 Chapter Contents

Starting with a basic overview of the power system and the relay, this paper will further divest into communication interfaces of a relay in chapter 2. Different communication technologies are addressed in the following chapters and Smart Grid communication requirements and challenges related to the relay will be discussed. In chapter 3, the discussion will focus on the required technology, opportunities in communication, and challenges for next generation protection and control relay.

1.3 Technical Background

1.3.1 Power Industry Overview

In North America, utility companies function independently from each other and are classified into four different categories: investor-owned, publicly-owned, cooperatives and Federal utilities. According to the information from the U.S. Energy Information Administration, there are about 210 investor-owned, 2,009 publicly-owned, 883 consumer-owned cooperatives, and 9 Federal electric utilities. Investor-owned utilities (IOU) own more than 38% of the generation capacity in the US and serve about 71% of end consumers.[1] Each type of utility has distinct characteristics and has different interests and needs.

The power industry can be segmented into generation, transmission and distribution of electricity. From the generation of electric power, the voltage is transformed to higher voltage to reduce power loss during transmission. Then, the electricity is distributed using power lines and goes through the substation to step down to the voltage level that is suitable for each customer. The voltage can range from hundreds of kilovolts at transmission lines all the way down to 120 to 240 volts for household customers. This wide range of power voltages can be classified into high, medium and low voltage, and the electrical equipment companies also manufacture and manage products in those groups. As high-voltage distribution is located at upper levels in the system and bears higher failure cost, the price of the devices in the high-voltage segment is the most expensive with additional safety features and functionalities among these three groups. Medium and low voltage level products are used in lower levels of the system mostly for distribution of electricity to customers. With a lower voltage level and less impact on the entire system, products for medium and low voltages usually have lower prices. Historically, electricity and information moved in one direction, from generation to transmission to distribution to customer, and there was not much need for communication exchange among different power product groups within ABB. This resulted in separation of the R&D and product development processes for each product group.

1.3.2 What is a Protection and Control Relay?

The main function of the relay is to detect any abnormal current or voltage at the transmission line and to protect the power system by controlling the circuit breaker to disconnect the line before a substantial or even catastrophic failure occurs. Another important function of the relay is to provide information, such as a failure and its location by monitoring and analyzing the situation. This information can be used promptly to maintain the device when necessary and analyze the fault detection and protection scheme for future safety. Early protection and control relays were electro-mechanical (EM) and performed only one function per device. Microprocessor-based (MP) relays are widely used today. These MP relays perform multiple functions within one device, and the number of features and functions has been increasing rapidly. In addition, more communication options are available in order to support increasing functionalities and features. Depending on the voltage level and applications, the characteristics of the relay could vary significantly.

Figure 1.1 is a simplified version of the microprocessor-based relay. Typically, the relay for distribution automation in medium voltage substations is connected to instrument transformers receiving analog voltage and current and monitoring the health of the system. Furthermore, it can also communicate with different sensors and devices using analog binary and digital inputs for the information such as humidity and temperature. Analog inputs are processed to digital formats in order to be usable by various electronic components including the microprocessor. The microprocessor mainly runs applications using the processed data and can be supported by RAM, ROM, FPGA and/or DSP. The relay can generate output to the circuit breaker to protect and control the line, if necessary. Additionally, the relay can generate information for monitoring purposes and for the supervisory control and data acquisition (SCADA) system. Thus, the communication interface is another important module within the device.

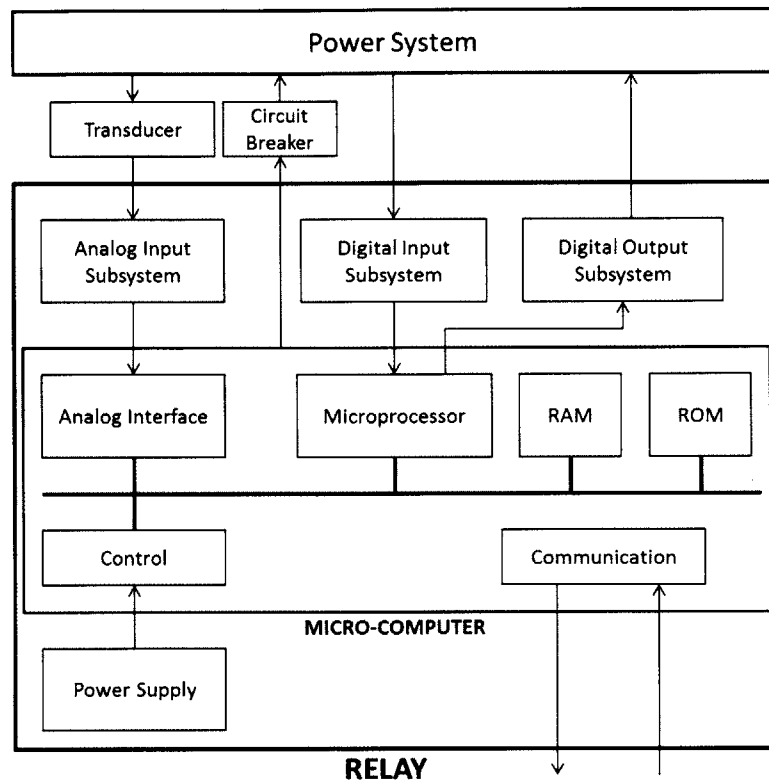


Figure 1.1 Relay Architecture Overview, adapted from [2]

As shown in Fig. 1.2, the power system contains different control layers. Note that the figure is a simplified representation of the system. The protection and control relay belongs to the bay layer as one of the intelligent electronics devices (IEDs). The relay communicates with different processing units including circuit breakers, sensors and transformers to obtain information and also to provide necessary commands. Furthermore, the device communicates with an upper layer providing status and data to the SCADA system. Note that with the implementation of Smart Grid, now the relays can share their status with each other using Genetic Object Oriented Substation Events (GOOSE) messaging under IEC 61850 standards. Details of Smart Grid related topics will be covered in later sections.

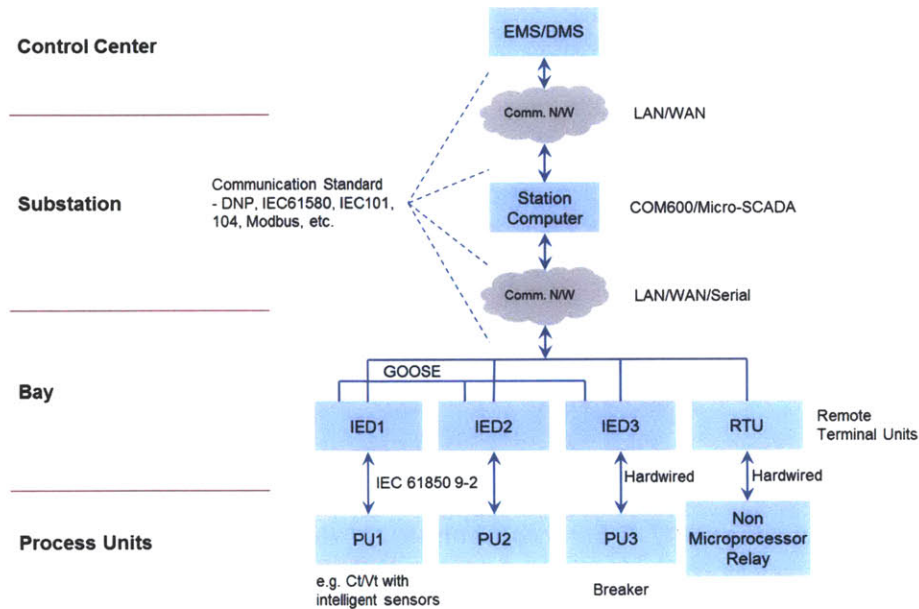


Figure 1.2 Overview of the Power System Control Layers, generated by ABB

1.3.3 History of Relay Technology

Electromechanical (EM) relays were originally used to protect power lines and the system. Traditional electromechanical relays could only perform a single function and thus each system circuit required multiple relays for various applications. Different types of EM relays such as single, two- and three- input types could be implemented for various applications. Analog voltage or current flows through the input of the EM relay and triggers the system if there is an abnormal situation. If the abnormality exceeds the set limit, then the relay signals the fault and takes appropriate actions, such as opening or closing the circuit breaker. Figure 1.3 shows an example of an electromechanical relay produced by ABB. With development of the silicon industry, solid-state technology using discrete electronic components was introduced in the early 1960's to the power system. This new technology brought numerous benefits over electromechanical relays including increased precision, reduced maintenance and faster operation.[2]



Figure 1.3 Electromechanical Relay, ABB

Microprocessor-based relays, which are dominant in recent applications, were first introduced in the 1970's with the advance of Very Large Scale Integration (VLSI) and software technology. Even though these relays had the capability to perform complex algorithms and applications, they had functionality similar to early electromechanical and solid-state relays.[2] Microprocessor-based relays with multiple functions were introduced in the late 1980s, which started transforming the industry significantly. Along with a drastic cost improvement, multifunction relays came to include monitoring and more controlling features available for a single device. Along with the advance in silicon and communication technology, the function of the microprocessor-based relay has improved significantly. From the passive device that receives inputs and simply generates outputs, the relays have become smarter and more active. As shown in Fig. 1.2 from the previous section, the relay can communicate with different layers and devices to effectively monitor, protect, and control not only a single line but the entire system collectively. Table 1.1 shows the strength and weakness of microprocessor-based relays compared to previous electro-mechanical technologies.



Figure 1.4 Microprocessor-based Relay, ABB

Strength	Weakness
Multifunction	Short life cycle due to obsolescence with fast technology development
Reduced Cost	Transient susceptibility
Customization	Setting and testing complexity
Panel space saving	
Reduced burden on instrument transformer	
Enhanced reporting	
Self-monitoring and self-healing	

Table 1.1 Strengths and Weaknesses of Microprocessor-based Relays [2]

Recently, with an increasing interest in Smart Grid, the protection and control device is now facing a new era with highly complex and integrated communication systems. There have been several changes and additions in communication recently, but the communication requirements for future relay products are expected to increase significantly. As Doug Voda from ABB mentioned, the relay is moving from “protection device with communication capability” to “multipurpose communication device with protection function,” which indicates the importance of the communication capability of the device. To accommodate the need and requirements of a new power grid system, communication interfaces and the protective relay will be increasingly complicated with multiple functions. However, with the conservative and diversified nature of the power industry, implementation of advanced communication technologies, such as wireless, will face challenges as well.

1.3.4 Different types of Protection and Control Relays

Relays, or more commonly known as IEDs these days, can be divided up into different categories depending on where they are used: There are distribution feeder, recloser, transmission, transformer, generator, bus, and motor relays that protect and control the power system. Figure 1.5 shows a diagram of typical power system from generation all the way down to distribution.

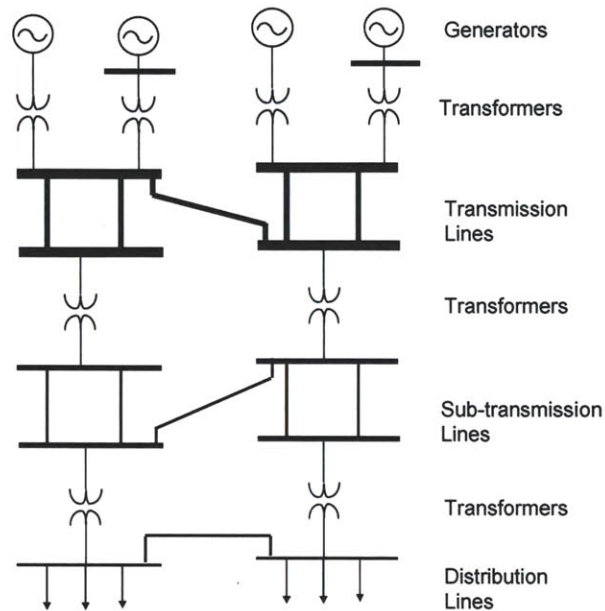


Figure 1.5 Typical Power System, ABB

For transmission or higher-level relays, failure of the device causes significant damage to the power grid as it impacts all subsequent connections. Since the cost of a power outage is significant, the relay has more hardware and communication capabilities compared to distribution feeder and lower level relays. The simultaneous tripping in transmission system is critical as there can be sources at both ends of the line – otherwise, system stability can be affected. This is achieved by direct communication between relays using different physical communications media such as fiber optics and leased lines. Cellular networks with high bandwidth such as 4GLTE can be used as an alternative. However, these communication options are not required for feeder relays.

On the other hand, characteristics of distribution feeder relays are low price with limited communication and hardware capabilities. These relays mostly reside within the substation controlling circuit breakers using information from sensors. Simultaneous communication between relays is not supported or used for feeder relays, as they are located close to the customers. As the cost of failure for feeder relay is relatively low compared to IEDs in a higher voltage level, feeder relays have limited hardware and communication capability mainly to maintain a low and competitive price. The thesis will focus on the analysis of the communication interface and potential opportunities in distribution-level relays.

With the implementation of Smart Grid, utilities are obliged to use alternate power sources in their power grid. This will result in distributed power sources at the distribution level using wind and solar power farms, which will demand more communication capabilities from feeder relays. With the addition of distributed power sources, the feeder relays will be required to communicate with each other directly to effectively protect and control the power system. This may result in implementation of a more comprehensive communication system, which is currently under development. However, currently implementation and change for feeder relays are unclear.

2 Communication for Distribution Feeder Relay

2.1 Current Microprocessor Distribution Feeder Relay Analysis

2.1.1 Microprocessor Distribution Feeder Relay Communication Overview

An important aspect of understanding communication options for next generation protection and control relays is the analysis and characterization of the communication interfaces of the devices. Relays have evolved from one-, two- or three-input electromechanical relays with simple output signals, to microprocessors that support various inputs and outputs to perform multiple functions. Along with the development of hardware and software technology, protection and monitoring features have been evolving. For example, SCADA systems have been implemented in power systems to aggregate information, and various distribution automation features have already been implemented for protection and control purposes. Furthermore, recent protective relays can communicate with each other using GOOSE messaging over Ethernet communication under the IEC61580 communication protocol. Figure 2.1 shows a simplified version of the protection and control feeder relay interfaces. Note that the interfaces have wide variations in connection type, input type, distance and characteristics.

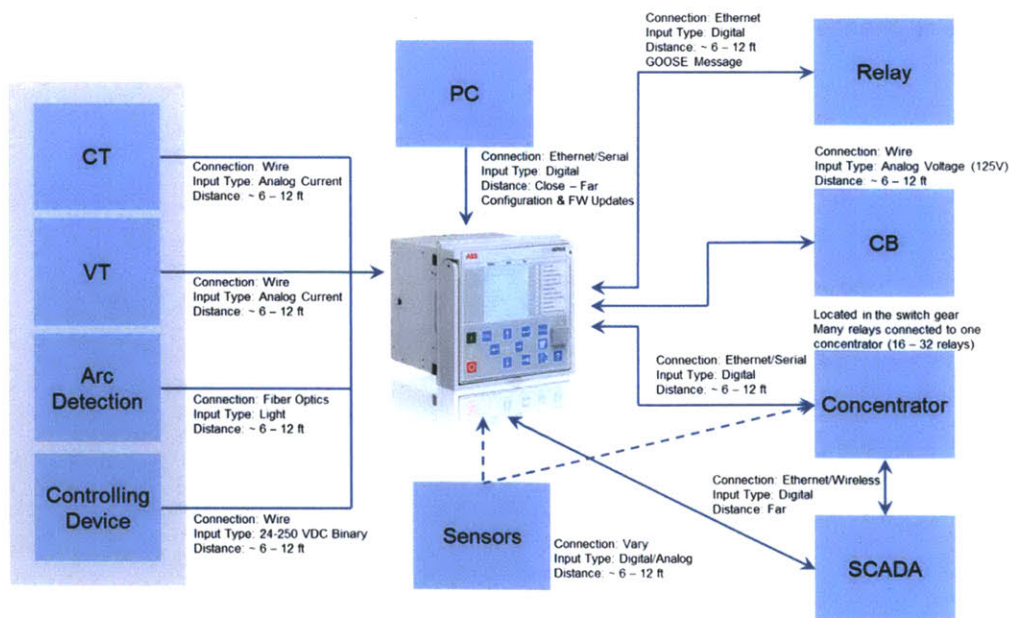


Figure 2.1 Current Distribution Feeder Relay Communication Interface Overview

2.1.2 Communication Interface Analysis & Attributes

A more detailed analysis of the interfaces can be found in Table 2.1. Refer to Appendix B for more explanations of the numbers and parameters. The following list is the specifications for analyzing individual communication channels used in Table 2.1:

- a. Connection: Current communication medium used such as copper wire and fiber optics.
The interface can be connected through copper wire for analog inputs or for Ethernet or serial communications. Fiber optics can be used for arc detection but also for replacing copper wire for digital communications.
- b. Input Type: Type of communication input. Some examples are analog, binary and digital.
Binary refers to an input that has either 1 or 0 in the analog domain.
- c. Distance: Average communication distance. Distance can vary from substation to substation and depends heavily on the implementation of utilities. This distance will provide coverage requirements for communication technologies.
- d. Type of Connection:
 - a) Direction of information: Uni- or Bi-Directional
 - b) Connection Type: Polling- or Event-driven
- e. Throughput (Baud Rate): Minimum required data rate for communication
- f. Security: Security requirement for the communication.
- g. Reliability: Reliability requirement for the communication.
- h. Integrity: Applicable for digital communication. Checking whether the right message is received. (e.g. DNP 32 bits CRC check)
- i. Latency: Tolerance on the delay of information/data received through the communication channel
- j. Real Time: Real time requirements of the communication

Point A	Point B	Connection	Input Type	Distance	Type of Connection		Throughput	Security	Reliability	Integrity	Latency	Real Time
					Direction	Connection Type						
Instrument Transformer	Relay	Copper Wire	Analog Current/Voltage	4-1000 ft.	Unidirectional	Continuous	200K - 1.5 Mbps	High	High	High	Low	High
Arc Detection	Relay	Fiber Optics	Light	6 - 12 ft.	Unidirectional	Event-Based	> 1 Gbps	High	High	-	Low	High
Relay Binary Input	Relay	Copper Wire	24-250 VDC	4-1000 ft.	Unidirectional	Event-Based	Low (<1 Kbps)	High	High	High	Low	High
PC	Relay	Ethernet/Serial	Digital	6 - 12 ft.	Bidirectional	Event-Based	200-500 Kbps	Medium	Medium	Medium	High	Low
Concentrator	Relay	Ethernet/Serial	Digital	6 - 200 ft. (Within Substation)	Bidirectional	Event-Based	200-400 Kbps	High	High	Medium	Low	High
		Fiber Optics		1 - 25 miles (Multi location)								
Relay Binary Output	Relay	Copper Wire	125 VDC / 120-240 VAC	4-1000 ft.	Unidirectional	Event-Based	Low (<1 Kbps)	High	High	-	Low	High
Relay	Relay	Ethernet	Digital (GOOSE)	6-200 ft.	Bidirectional	Event-Based	30 Kbps	High	High	Medium-High	Low	High
Sensor	Relay	Various	Analog/Digital	4-1000 ft.	Bi/Unidirectional	Event-Based/Continuous	Vary	Medium	Medium	Medium-High	Medium	Low
SCADA	Relay	External Wireless	Digital	6 - 200 ft. (Within Substation)	Bidirectional	Event-Based	200-400 Kbps	High	Medium	High	Medium	Medium
				Far (> 100 miles)								
Front Panel	Relay	Cable/Ethernet	Digital	0 - 10 ft.	Bidirectional	Event-Based	Low (<1 Kbps)	High	Medium	Low-Medium	High	Low

Table 2.1 Current Feeder Relay Communication Interface Details

2.1.3 Communication Interface Details

Appendix B shows a detailed analysis of general communication interfaces for protection and control relays. Note that depending on the utilities and their applications, these characteristics could vary. Many of the attributes for the interfaces are hard to characterize and thus they were estimated by internal expertise in ABB. An important thing to note in Table 2.1 is that current relays have a variety of interfaces with different characteristics. Furthermore, each of these interfaces can vary case-by-case depending on the implementation. This wide variation is one of the major difficulties in implementing a new communication technology for the product. As utilities, especially ones in NA, often use products from different vendors and have freedom and flexibility in their implementations, the ABB medium voltage group also has to be flexible and provide options for all their customers' needs. Explanations of communication interfaces around the relay follow:

1) Instrument Transformer to Relay

The primary role of the relay is to detect any abnormal condition in the power line. The connection from current and voltage instrument transformers to the relay provides information about the state of current and voltage on the line. Depending on the application, this information can detect overcurrent, undercurrent, overvoltage and/or undervoltage conditions. These connections are direct links and the scaled analog voltage and current come as the input to the relay. Analog information is sampled and converted to digital format inside the relay. Thus, it is possible to convert the voltage and current to digitized data early and send information through Ethernet to the relay. High security, reliability and low latency are critical for this connection.

2) Arc Flash Detection to Relay

Arc detection is communicated using fiber optics and detects an event involving arc-flash. Arc-flash is a "dangerous condition associated with the release of energy caused by an electrical arc." [3] Arc-

flash detection is used to prevent personal injury, equipment damage and system outage by detecting the arc flash and interrupting power. This channel specifically uses arc-flash light as a signal to sense the event, requiring high security and reliability and low latency. Fiber optics can provide low latency and fast response suitable for this communication.

3) Relay Binary Input to and output from Relay

There are various sensing devices with binary inputs ranging from 24-250 Vdc. Even though these inputs and outputs are binary, 0 or 1, the voltage range is in the analog domain. One example of relay binary output is the communication interface to the circuit breaker. The primary function of the relay is to protect the power line according to the information provided from the instrument transformer using a circuit breaker. When a relay detects an event and decides to either close or open the power line, it creates an analog output of 125V to the circuit breaker that will trigger the switch. This analog voltage is generated within the relay and directly connected to the circuit breaker. These channels are connected to critical protection and control devices and thus require high reliability and security with low latency.

4) Relay to Relay

Smart Grid applications require a two-way and complex communication structure among devices. The IEC 61850 protocol is one of the initiatives to develop standard Smart Grid technology. As one part of the protocol, it specifies communication methods among protective relays using GOOSE messaging. GOOSE messaging enables the relays to share basic information and understand the state of other relays. Depending on the application implemented for this communication, the channel can have different requirements. However, to guarantee correct information transfer and to reduce risk, high security and reliability are recommended.

5) Relay to SCADA

In current protection and monitoring schemes, a relay sometimes talks directly to a SCADA system but often goes through a concentrator to be connected at a higher level. However, with increasing communication complexity and requirements, relays might be required to communicate directly with SCADA or central systems. As SCADA systems can exist within a substation but also far away from the device, the distance requirement can vary significantly from case to case. Compared to protection related channels, relay to SCADA will not require a high level of reliability and latency, but will require having high security and integrity to make sure correct information is securely sent to the control center.

6) Relay to Concentrator

The concentrator communicates with an upper-level system where it is connected to multiple relays. Relay to concentrator distance can vary depending on where the concentrator is located. Currently, this channel is mostly connected using a serial or Ethernet copper wire connection, but fiber optics is also available for some products. This communication channel is critical for high-level data management and control of information. Thus, the relay to concentrator channel requires high security and reliability and low latency.

7) Sensor to Relay

With increasing detection and sensing schemes added to power devices, there are and will be more and more inputs to a relay. Some of the inputs will be analog but others will be digital. For example, in order to enhance the quality of the various devices in substations, asset health monitoring sensors can be implemented to monitor behavior of the devices. In order to reduce the cost of the sensors and increase integration of all the devices, these sensors might not have processing capabilities to transform raw data and create digital signals. Thus, this raw information will be required to be processed within the substation, potentially at the concentrator and/or relay. These

new sensors are mostly for protection and maintenance of devices by analyzing their behavior. Thus, reliability and security of these channels can be relaxed, as they are not directly related to protection and control of the power system.

8) PC to Relay

Utilities demand easier control and configuration of protective relays by easier access to the devices. Even though it is possible to access the device remotely by using existing networks, operators at the substation have to manually and physically connect the device and computer to access information in the relay. ABB can provide wireless remote control of the relays usable by the operators in the field. Depending on the need, this could require wide area and/or personal area network. This channel needs enough security and reliability to prevent unauthorized personnel from accessing the information. High throughput is preferable for fast data transmission, but the reliability and latency requirement can be relaxed for this channel. There should be encryption of data and authentication of users to provide enough security to prevent unauthorized access.

9) Front Panel to Relay

Microprocessor-based relays have a front panel that a user can manipulate to control and configure the device. A detachable front panel is not a typical communication interface for a current relay. There is an opportunity to separate the front panel from the relay and make it an external device. By reducing the number of parts in the relay, this will add flexibility in design while reducing device failure and cost due to the front panel. Various applications can be implemented such as one panel to multiple devices and wireless remote access using an external front panel. Communication requirements for this channel are not stringent but require higher security to prevent unauthorized personnel from accessing the relay and changing the configuration. Opportunities in this area will be discussed further in a later chapter.

2.2 Wired & Wireless Technology

2.2.1 Wired Communication Overview

Even before the Smart Grid was introduced, there was a need for a more reliable and secure monitoring and controlling system in the substation, which resulted in the deployment of distribution automation systems. Distribution automation requires that relays and other devices have a certain level of communication capability. Relays started as basic communications components with instrument transformers and circuit breakers using analog copper wire connections, but recent microprocessor relays support serial and Ethernet copper cable and fiber optic communication. By utilizing the existing power infrastructure, utilities can also send data over a power line. There has been recent research about improving PLC (Power Line Communication), which had throughput limitations in the past. A summary of the technology attributes can be found in Appendix A. Technologies discussed in the following sections will only consider digital communication using certain media.

1. Copper Cable

Copper wire is used for both serial and Ethernet communication. This is currently a common communication method, or medium, used in power systems for communication within a substation. Communication using copper wire, either serial or Ethernet, is relatively cheap to implement as the technology is mature and a large number of devices are available. Wired communications have high security and reliability characteristics as long as there is no physical breakage. Depending on the implementation, theoretical throughput for copper cable can range from 10 – 100 Mbps, which is sufficient to run most Smart Grid applications.

On the other hand, there are several challenges with communication using copper wire. Copper theft is one of the big problems in the industry, which can interrupt not only electricity flow but also the entire control and protection system. According to the estimates from the U.S Department of

Energy 2007 report, the economic impact of copper theft from utilities has totaled more than \$1 billion a year and it is projected to keep increasing.[4] As this can impact the entire protection and control system around the power grid, this is a major problem. Furthermore, even though the security of copper wire is higher than that of wireless technologies, it is possible to physically tap into the wire to gain access to the system. Lastly, inherent characteristics of electrical systems, including signal attenuation, electromagnetic interference, and radio-frequency interference, can cause implementation challenges for long distance communication.

2. Fiber Optic

Fiber optics is a technology that uses fiber cable as a medium and light as a signal for the communication. The basic properties of fiber optics are similar to copper wire, but fiber has improved performance in throughput, security, reliability and other attributes. Theoretically, fiber provides unlimited bandwidth while being almost impossible to tap into and interrupt the information. As fiber does not use electrical transmission of information, it does not have challenges that copper wire inherently has. As signal attenuation and interferences are small using fiber technology, it is possible to go longer distances securely and reliably.

Fiber technology still has several disadvantages with implementation as compared to other technologies. Similar to copper wire, implementing fiber optics requires developing and planning physical infrastructure to connect two points. This could be difficult in metropolitan areas or well-established areas with congested power and communication lines. Furthermore, fiber is also exposed to physical damage by intentional or natural events; this can be mitigated by implementing fiber optic communication underground. Due to the distinctive characteristic of fiber optics, it is difficult to have point-to-multiple-point communication or to add a device along the existing fiber route. This attribute increases security of communication while hindering scalability. Without careful planning, expanding the network infrastructure is not as easy for fiber technology as it is for

wireless. Considering these advantages and disadvantages, fiber optic is suitable for backhaul communication, the intermediate link between core and edge network. A summary of the advantages of fiber technology over copper wire is shown in Table 2.2.

Advantages	Disadvantages
System Performance	Relatively new technology
Greatly increased bandwidth and capacity	Expensive Transmitters and Receivers compared to electrical devices
Lower signal attenuation (loss)	Lack of standards in industry
Immunity to Electrical Noise	Difficult to implement point-to-multiple-point communication
Immune to noise (electromagnetic interference [EMI] and radio-frequency interference [RFI])	Requires physical infrastructure
No crosstalk	
Lower bit error rates	
Signal Security	
Difficult to tap	
Nonconductive (does not radiate signals)	
Electrical Isolation	
No common ground required	
Freedom from short circuit and sparks	
Reduced size and weight cables	
Resistant to radiation and corrosion	
Resistant to temperature variations	
Improved ruggedness and flexibility	
Less restrictive in harsh environments	
Overall System Economy	
Low per-channel cost	

Table 2.2 Strengths and Weaknesses of Fiber Optics compared to Copper Wire [5]

2.2.2 Wireless Communication Overview

Not all communication channels can be digitized and converted to wireless communication. Using wireless for certain applications might not be financially and/or technically feasible given the high capability of fiber optics and other wired technologies. Moreover, even in Smart Grid implementations with complex digital communications, wired communications, such as copper wire, will still play a

significant role within the system. Table 2.3 shows a brief comparison of the strengths and weaknesses of wireless communication. Note that each technology has different characteristics and the table shows a general overview. Also, characteristics of various wireless technologies can be found in Appendix A along with wired technologies.

Advantages	Disadvantages
Low installation cost in general	Susceptible to interference and noise, especially for unlicensed spectrum
Mobility of devices and implementations	High cost for licensed frequency
Flexible coverage to remote area	Inverse relationship in coverage and throughput
Fast implementation over wire	Relatively easy to tap into
High scalability	Additional security features required

Table 2.3 Advantages and Disadvantages of Wireless Communication [5]

1. Private vs. Public

There are several ways to classify communication technology. Depending on the ownership of the infrastructure, it can be separated into public or private communication. Private communications provide more secure and reliable communication where utilities have the capability to configure and control the infrastructure. However, in order to build up private communication, a utility has to make large initial investments to build the system. On the other hand, public communications, such as cellular, provide an easier solution for utilities to tap into existing infrastructure. Communication service providers are responsible for maintenance and other costs. However, even though the initial capital requirements can be low, many public communications require monthly or regular fees that can cost more in total. Furthermore, utilities cannot guarantee the operational quality of the service including security, reliability and control. Some technologies such as WiMAX can be operated either publically by using towers built by others or privately by building private towers. There are both advantages and disadvantages for public and private networks and thus utilities should carefully analyze their applications and choose the right solution for them.

2. Licensed vs. Unlicensed

Wireless technologies utilize dedicated frequencies for their communications. This frequency spectrum is defined in standards and all devices for that technology use the same frequency band. The spectrum of the technology can be either licensed or unlicensed. Single communication technologies can have multiple frequency bands with both licensed and unlicensed bands. Unlicensed bands can be used by anyone, with certain restrictions, thus they are cheaper to use. However, as anyone can access and use the band, it is possible to have interference and congestion in the field, damaging the performance of the communication. This is especially undesirable in the metropolitan area, where lots of people are using various wireless devices. However, there are different techniques, such as Orthogonal Frequency-Division Multiplexing (OFDM), that have been developed to mitigate interference among channels using the same frequency. On the other hand, a user needs to reserve the frequency band to use the licensed frequency. By reserving the licensed frequency, it is possible to reduce interference with other transmitters. However, reserving licensed frequencies is expensive and the devices are expensive as well. For applications within a substation, there is low interference potential as there is no one around and an unlicensed frequency band can be used with a cheap implementation cost. On the other hand, communication in metropolitan areas can be done using licensed frequencies to prevent interference. However, it might be difficult to obtain a licensed frequency due to high demand.

3. WAN, LAN, HAN, & PAN

Another way of classifying wireless technologies is by their geographic coverage capability. Depending on the coverage, they can be divided into several categories. Starting with the broadest coverage group, WAN stands for Wide Area Network, LAN for Local Area Network, HAN for Home Area Network and PAN for Personal Area Network. There are other names, such as Near Field Communication (NFC), Field Area Network (FAN) and Metropolitan Area Network (MAN) that have similar meanings to those in the above

list. In this paper, the technologies are divided up into three groups, which are listed below. The technical information is mostly adopted from [6].

- NFC (Near Field Communication) or PAN (Personal Area Network): NFC or PAN technologies are used for communication within small area. These technologies can be used mostly for communication among devices within the substation for data transfer. Depending on the application, the communication requirement will vary. NFC communication will be used for applications within the substations that do not require broad coverage and complex communication infrastructures.

a. ZigBee

ZigBee is intended for wireless control and monitoring features that need low power and low data rates. ZigBee provides near field communication coverage of up to around 100m with low cost and power. This technology uses the unlicensed spectrum of 868MHz, 915MHz and 2.4 GHz and 20 – 250 kbps data rate. ZigBee can support 255 – 65000 network nodes supporting star, tree and mesh topologies with the ad-hoc, or decentralized, network. For security, the technology supports 128 keys for security features. Furthermore, ZigBee could be good for applications requiring low power and data, which can be suitable for relay-to-relay communication. However, ZigBee raises some concerns when it is used in a power system. Compared to other technologies, ZigBee is not widely used in the industry and is relatively immature for use in substations. Relay-to-relay communication requires <50 kbps, but for other digital channels such as relay-to-concentrator, the throughput requirement can go up to 400 kbps or more. The capacity of ZigBee, especially in throughput, will be the major challenge in future applications to substations.

b. Bluetooth

Bluetooth provides short-range radio frequency communication with low power consumption. It is part of the 802.15.1 standards using the 2.4-2.4835 GHz unlicensed spectrum. The coverage can vary from 1 – 100m depending on the standards with around 721 kbps of data rate. The technology supports both point-to-point and point-to-multipoint communication. Bluetooth is widely used for peer-to-peer communication involving portable devices. Compared to ZigBee, Bluetooth provides higher throughput, but supports fewer node connections. Also, the spectrum frequency can interfere with other WLANs sharing the same frequency. Lastly, for substation device-to-device communication, security is the biggest challenge and concern. As Bluetooth does not have a centralized system administering the connections, security of the information will be questionable.

- HAN (Home Area Network) or LAN (Local Area Network): HAN or LAN technologies are used for communication covering a wider range than NFC or PAN. This technology can cover networks that require greater communication distances.

- a. WiFi or Wireless LAN

WiFi is an IEEE 802.11-based wireless LAN that has various versions for different applications. The technology is easy to install and less expensive compared to other wide-area technologies. WiFi has coverage of 75 – 150 m with throughput ranging from 11 to 600 Mbps, depending on the standards, and frequency spectrum using 2.4 and 5 GHz. Version 802.11i provides an enhanced security feature using Advanced Encryption Standards (AES). The IEC 61850 standard proposed that Ethernet-based communication networks, such as wireless LANs, are best suited for the interoperability of substation automation systems.[6] WiFi can interfere with other wireless devices, especially in the 2.4 GHz band. This creates challenges for the reliability and

availability of the signal. For power systems, a high voltage environment can create electromagnetic interference that decreases data throughput.

b. WiMAX

WiMAX is a part of the 802.16 standard created to achieve worldwide interoperability for microwave access. Regarding spectrum availability, there are 2.3, 2.5, 3.5 and 5.8 GHz bands that are licensed. There is also a 5.8 GHz unlicensed frequency. The data rate can go up to 70 Mbps and distances can be as large as 48 km. Note that distance and throughput are inversely proportional to each other. WiMAX can be considered a large-scale version of WiFi with more throughput, coverage and features. This technology is good for stationary communication. Depending on the implementation and coverage of WiMAX towers, it can serve as LAN or Wide Area Network (WAN).

WiMAX communication requires building communication towers or stations, which requires huge capital investments. Thus, utilities can either decide to lease the service from existing towers or build their own private network. WiMAX supports point-to-multipoint communication where a single tower can serve hundreds of users. For communication distances of less than 10 km, it is possible to serve devices without line of sight. However, for communication distances longer than 10 km, line of sight is necessary. Furthermore, weather and other wireless devices can impact the quality of the signal and damage throughput and reliability.

- WAN (Wide Area Network): WAN technologies are used for communication covering wide areas with distances of over 1 KM. This technology is responsible for communication among substations and central control centers. This will be one of the key drivers for Smart Grid technology, as it will enable more interactive protection and system monitoring of wide areas.

a. 2G, 3G, 4G LTE

Cellular networks, starting with the 2G CDMA and GSM networks, are another potential technology for applications requiring long distance communication. With the development of smart phones and the use of data in mobile devices, 3G, 4G and LTE networks are widely used in the US. Moving up generations from 2G to 4GLTE, the data throughput increases to support wider use of data by mobile device users. 900M – 1.8 GHz licensed frequencies are used for 2G, 1.9 GHz licensed frequencies for 3G and various spectrum frequencies can be used for the 4G network. Data rate varies from 14.4 Kbps for 2G up to 5 – 12 Mbps downlink for 4G LTE.[7] The network consists of low power wireless transmitters that form a cell. Figure 2.2 shows the 3G and 4G LTE coverage map for Verizon Wireless in the US. Note the figure only shows high data rate services. Including the 2G network would increase the coverage. As network infrastructure already exists and it covers wide areas, utilities can simply tap into the existing infrastructure by using the service from the carrier. As this network is fully provided and maintained by the carrier, there will be no maintenance cost for the utilities.

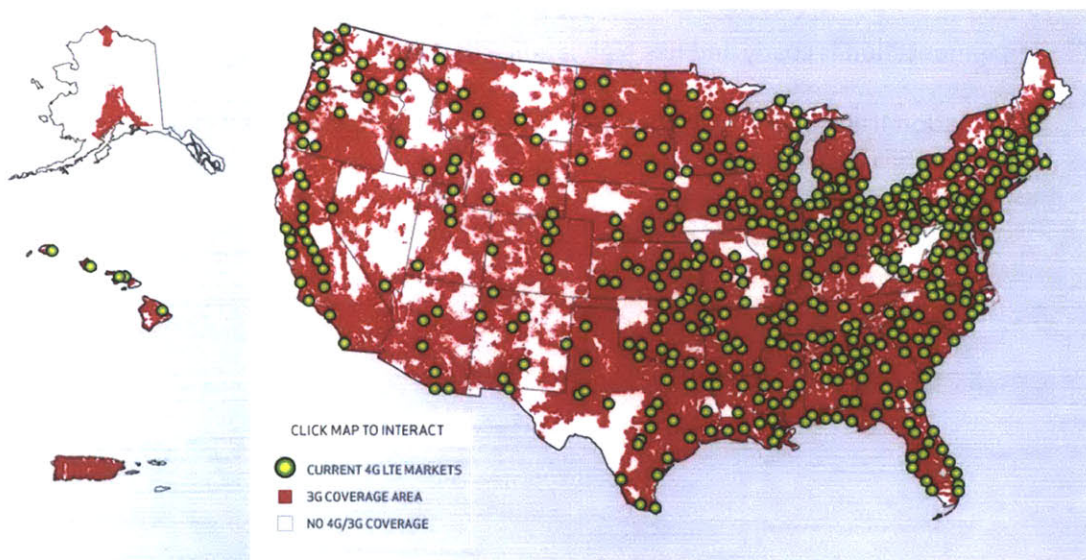


Figure 2.2 Verizon Wireless 3G/4GLTE Coverage Map, Verizon Wireless Website

With these benefits, there still exist challenges for cellular networks. Even though there will be no capital investment required to build up network infrastructure, monthly fees for the service

can be costly. As different customers use this network heavily, reliability can also be an issue with time delay and call dropout. Furthermore, it is still questionable that public cellular networks can provide enough security for critical power grid information with enough prioritization features to provide necessary requirements for Smart Grid implementations. However, working together with the carrier, cellular networks can be a viable option for long distance communication in Smart Grid applications.

b. Satellite

Satellite is another wide area communication option that can be used for Smart Grid applications. Theoretically, this communication can reach out to remote areas, as the transmission station is located in space. Throughput is in the range of 50 Kbps and has the capability to broadcast the information to multiple points. Different bands exist, e.g. the C, Ku and Ka bands, with different frequency bands ranging from 4 to 30 GHz. In order to enhance security, information has to be encrypted for protection. Satellite communication implementation is costly and has high latency that might not be suitable for timing critical information transfer. Furthermore, low data rate and interference will be other challenges if it is used.

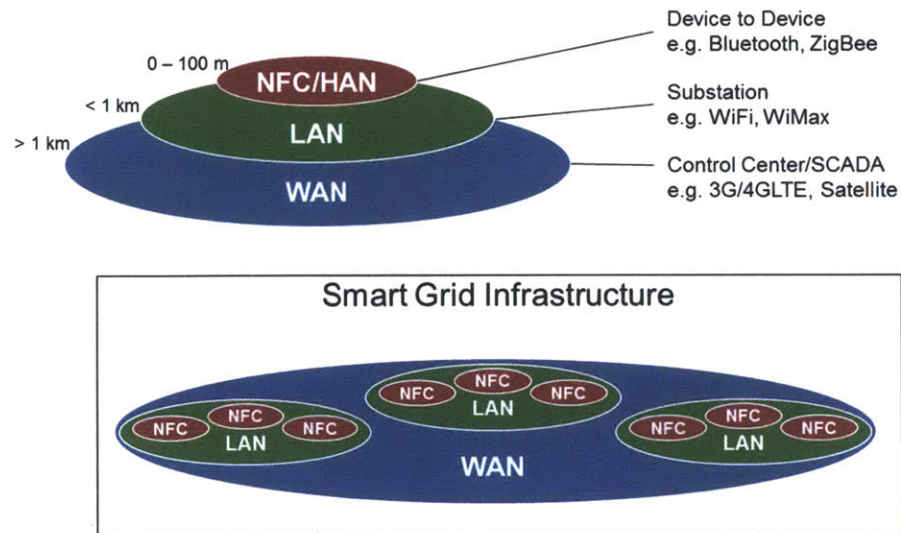


Figure 2.3 Communication Technology by Coverage and Smart Grid Implementation

Figure 2.3 shows the summary of wireless communication and possible Smart Grid infrastructure using different technologies by coverage. Considering the importance of reliability and security of communication, multiple technologies can be used for a redundant network with a combination of wired and wireless technologies. Each utility will find technologies that fit their implementation needs for new features and functions, as there is no uniform communication standard and guideline required to be followed by utilities. Table 2.4 provides detailed analysis and comparison of communication technologies.

					Ethernet					PLC			
	WiFi (802.11)	ZigBee	Bluetooth	Fiber Optics	Copper Wire	2G	3G	4G/LTE	WiMax	Narrowband	Broadband	Satellite	Leased Line
Type	Wireless	Wireless	Wireless	Fiber Cable	Land Line	Wireless	Wireless	Wireless	Wireless	Power Line	Power Line	Wireless	Land Line
Ownership	Private	Private	Private	Private	Private	Public	Public	Public	Private/ Public	Private	Private	Public	Public
Throughput (Data Rate, in kbps)	11000 - 600000	20-250	721	> 1G	10000- 100000	14.4	384-2000	100000 (Down) 50000 (Up)	75000	upto 500	1000	56	1500
Coverage	75 - 150 m	30 - 50 m	1 - 100 m	Far	< 100 m (indoor)	1 - 10 km	1 - 10 km	1 - 10 km	10 - 50 km (LOS) 1 - 5 km (NLOS)	-	-	Wide	Far
Spectrum Availability	2.4 GHz (G, B) 5 GHz (N)	2.4 GHz 868-915 MHz	2400-2480 MHz	- -	- -	900-1800 MHz	1.92-1.98 GHz 2.11-2.17 GHz	Multiple	2.5, 3.5, 5.8 GHz	- -	- -	Multiple	- -
Cost	Low-Medium	Low	Low	High	Medium	Medium	Medium	Medium-High	Medium	Low-Medium	High	High	Medium-High
Security	Medium	Medium ⁴⁾	Low- Medium ⁵⁾	High	High	Medium	Medium	Medium-High	Medium- High	Medium	Medium	Medium	Medium-High
Reliability	Medium-High	Medium- High	Medium	High	High	Medium	Medium	Medium-High	Medium- High	Medium	Medium	Medium	Medium-High
Life Cycle	Mature	Emerging	Mature	Mature	Mature	Mature	Mature	Emerging	Mature	Mature	Emerging	Mature	Mature
Technology Risk	Low	Medium	Low	Low	Low	Low	Low- Medium	Medium	Low- Medium	Low	High	Medium	Low
Latency	Medium	Low- Medium	Medium	Low	Low- Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Low-Medium

Table 2.4 Wired & Wireless Technology Details

2.3 Smart Grid Technology

2.3.1 What is Smart Grid?

The traditional power system mostly consists of one-way communication and data flow from the power generation to customers. Power is generated from a source that can be controlled reliably depending on the demand forecast. The voltage level is increased for transmission to reduce the power loss, and the distribution network feeds electricity to necessary places. Customers do not have much visibility over their electricity use, as traditional electricity metering doesn't provide real-time monitoring.

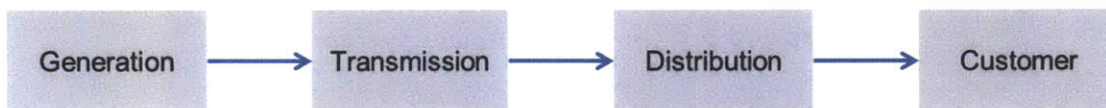


Figure 2.4 Traditional Power System

However, with continual increase in electricity demand and introduction of renewable energy, it is getting difficult to produce electricity efficiently and reliably without becoming “smart.” According to the US Energy Information Administration, electricity consumption in 2011 totaled nearly 3,856 Billion kWh, an increase of 13 times since 1950, and is expected to increase more rapidly. The current power grid might not support peak demand of electricity in the future, as customers use more and more electronic devices and electric vehicles. Furthermore, regulation is requiring utilities to use renewable energy as an alternative source of power that is hard to control and predict. Renewable power sources such as wind and solar depend heavily on day-to-day weather condition and cannot provide reliable and planned power to the customer without dynamic control and monitoring of electric usage. Given that the government is requiring utilities in the US to implement renewable energy in their power system, sophisticated and intelligent communication infrastructure will be desired by utilities. For example, in Oregon, renewable energy must provide 25% of the energy mix by 2025.[8] Lastly, consumers are getting smarter and want to know more about their power usage and potentially have control over it. Also, advanced metering will enable the reduction of electricity theft and improve efficiency of use.

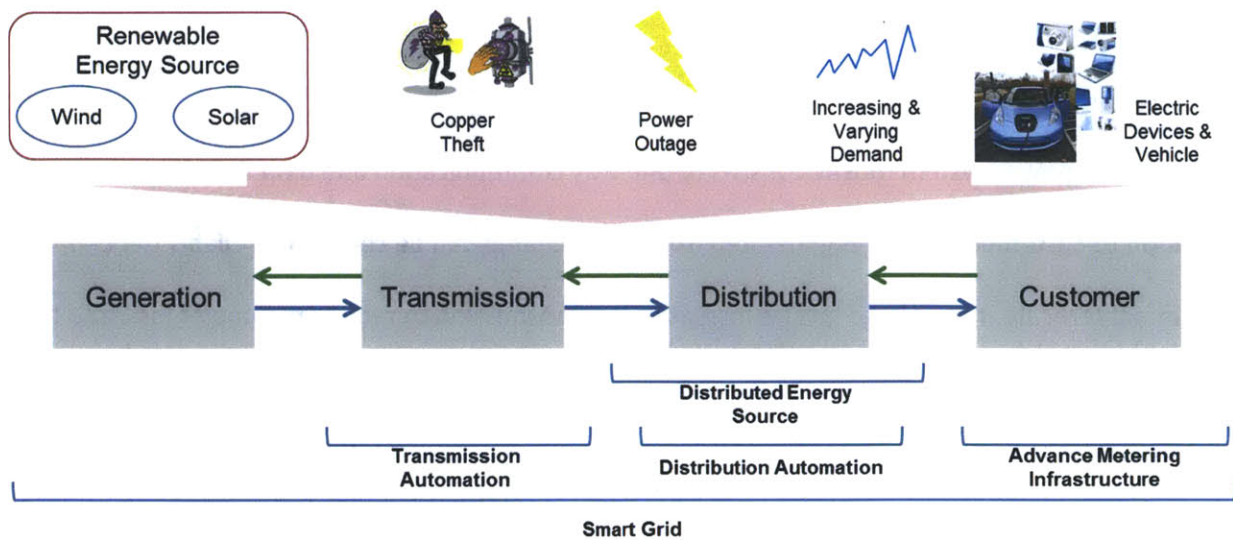


Figure 2.5 Smart Grid Power System

As shown in Fig. 2.5, with increasing power usage, high cost of power outage, copper theft, renewable energy sources, and other reasons, there is a need for the power grid to evolve and become smarter and more efficient. The main purpose of Smart Grid is to utilize and manage huge amounts of information available in the power system to better protect, control and monitor the grid. From an Electric Power Research Institute (EPRI) report to the National Institute of Standards and Technology (NIST) published in August 2009,

“the Smart Grid will be characterized by a two-way flow of electricity and information to create an automated, widely distributed energy delivery network. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level.” [9]

Unfortunately for electrical equipment manufacturers, the definition and scope of Smart Grid technology is still fluid. There have been various research and publications about the requirements, infrastructures and regulations about Smart Grid technology, but nothing is really determined and standardized industry-wide. The process of setting the stage for advanced communication infrastructure has been started, as evidenced by the progress of IEC 61850 communication protocol development, and

it will be gradually defined and specified more clearly. However, it is also possible that each utility company, state and/or country might require and implement a different infrastructure. If so, the ABB medium voltage group will have to stay flexible and proactive to meet the different requirements.

2.3.2 Relay Communication Requirements for Next Generation Power Grid

Implementation of new communication technology for protective relaying has to be carefully considered for the entire Smart Grid and future power system. Rather than optimizing an individual communication channel, which can result in diversification of various technologies used in similar applications, utilities and manufacturers should carefully examine the current and future communication channels and search for the technology that closely aligns with the requirements. Following is the list of critical communication parameters:

a. Throughput

Most wired communications, excluding power line communication (PLC), have sufficient throughput specification for the protection and control of relay applications. Fiber optics technology especially has extremely high throughput that can support any application. However, wireless technologies have a wide range of throughput specification. As different communication channels require different throughput for their applications, various communication technologies can be utilized as long as they meet minimum throughput requirements for the channel.

b. Geographic Coverage

The coverage for the communication mainly concerns wireless technologies. However, even for wired communication, coverage can be an issue when wiring cost is high or signal degradation is significant for long distance communication. For wireless communication, the technology can be classified as WAN, FAN or HAN depending on the coverage distance. Throughput and coverage are inversely proportional to each other. As shown in Fig.1.2, the power grid connects multiple layers of communications and has a

variety of distance requirements. Potential features for next generation feeder relay may include both short- and long-distance communication requirements and thus it is difficult to meet all coverage needs with a single communication technology.

c. Latency

The main feature of the relay is to monitor and control the electricity and to protect the power system. Thus, for features related to control and protection of the power line, the relay needs to react as fast as possible. In order to achieve this, communication technology for these features needs to guarantee fast response time. Thus, latency is one of the most important parameters for protection-related features. On the other hand, for certain non-timing critical functions such as firmware updates and data acquisition, latency requirements can be relaxed.

d. Security

Security is another critical parameter in protection and control devices as any security flaw can cause significant monetary and social damage. For wired communication, security mainly concerns encryption of the information and potential wire theft as information can be only accessed by direct connection. However, for wireless technology, data is sent out through space and anyone can potentially access it. Thus, it is critical to have an additional layer of security features to protect the system from any unauthorized access. Another important aspect of security is traceability of security breaks. This means capability of the system to trace and report any security break to prevent future threats.

e. Reliability

Power systems require high reliability, robustness and availability to reduce the risk of failure and power outage. In order to increase reliability of the power system, utilities need to use modern communication protocols, faster and more robust control devices, and embedded IEDs to enhance reliability and robustness. Wired and wireless communications have both strengths and weaknesses from a reliability

perspective. Wired technologies can guarantee high reliability until there is physical breakage or wire theft. In order to prevent this, wiring can be done underground. On the other hand, wireless technologies don't have to worry about physical breakage of the channel, but have inherent reliability issues. Depending on the spectrum frequency, signal penetration and degradation can result in reliability degradation. Furthermore, each wireless technology has a coverage restriction where the signal gets weaker towards the edge. In order to satisfy stringent reliability requirements for advanced protection and control applications, the hybrid system using both wired and wireless technologies could be a solution.

f. Quality of Service

Quality of Service, or QoS, can be defined in various ways, but it refers to prioritization of the information in this thesis. Power systems consist of large amounts of data, and this information will be utilized for protection, monitoring and control purposes with implementation of advanced power grid systems. In order to increase the response time and efficiency of the system, transferring information should be prioritized. For example, any information that indicates power outages should be processed and transferred first over other non-critical data.

g. Scalability

Previously, scalability of the communication system was not a challenge or requirement as communication infrastructure needed to cover only a small area of the network. However, many of the next generation applications for protection relays require large numbers of nodes and devices to be connected together throughout different layers of the power system. Increasing information and network complexity requires scalable communication systems. Furthermore, there should be enough flexibility to scale the system as new devices or additional systems are added. Communication systems

should also incorporate integration of advanced web services and reliable protocols with advanced functionalities.

h. Cost

The purpose of Smart Grid is to improve efficiency of the power grid and ultimately eliminate any power outages and provide electricity to everyone. However, in order to implement complicated and sophisticated Smart Grid applications, huge amounts of investigation are necessary. Utility companies, especially in North America, have the power to decide the implementation of Smart Grid applications and technologies. From the Newton-Evans survey, it is clear that cost is the most important factor for implementing the technology. Figure 2.6 shows the results of a survey asking utility companies about their data communication considerations.

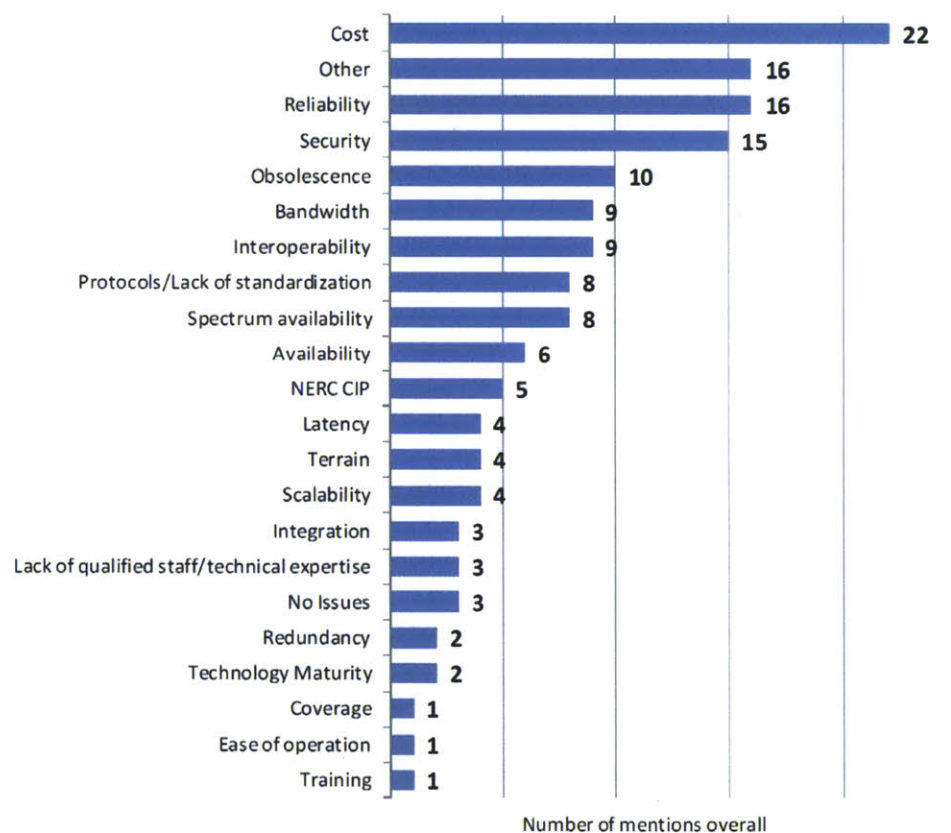


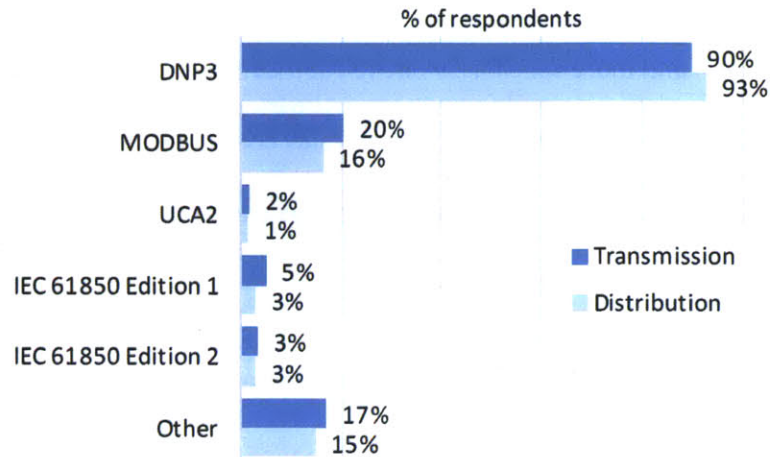
Figure 2.6 Survey result for data communication issues in Utilities [10]

There have been various papers discussing different communication implementations and opportunities for the entire power system and more specifically distribution automation in substations. Along with discussing a case study and research that is applicable to relay communication, this thesis will focus on understanding current microprocessor-based protective relays and search for opportunities and challenges in adopting the Smart Grid technology.

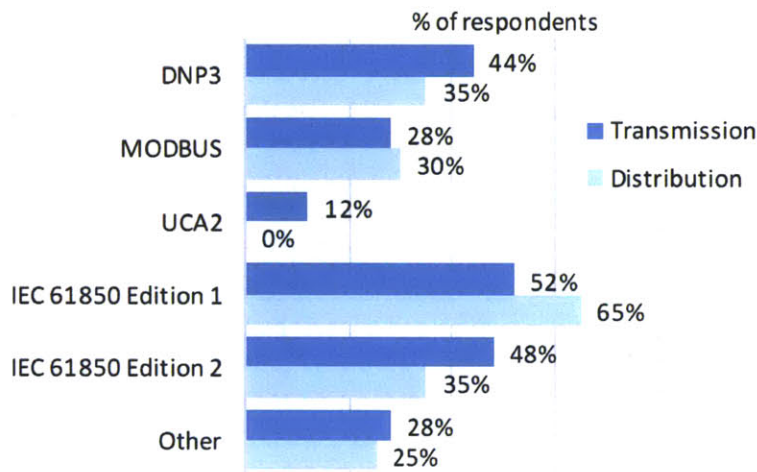
2.3.3 Communication Standards and protocols - IEC vs. ANSI Standards

Similar to the freedom in technology choices, utilities can choose standards that they want to use for their power system. In general, European utilities follow IEC standards whereas North American utilities use IEEE standards. Power utilities across the world utilize different practices and standards due to geographical and political variations. From Fig. 2.7, which lists the communication standards used in NA and international utilities, it is clear the DNP3 standard is dominant in North America while several standards are used quite evenly in the international utilities. In international power industries, IEC standards are heavily used in European countries and others, including DNP3, are used in non-European countries. As different standards require different communication layers and structures, the device needs to have a specific communication card that can support the system. This creates a wider variety of communication and system options combined with different communication technologies.

Multinational electrical equipment companies like ABB need to provide devices for various standards for customers all over the world. When Smart Grid communication standards and specifications are well defined for the utilities, power electronics devices, such as the protection and control relay, will also experience reduced variations in communication standards.



(a) North America Utilities



(b) International Utilities

Figure 2.7. Communication standards used in the utilities for (a) North America and (b) International Utilities [11]

Before pushing Smart Grid applications to the industry and actually implementing new technologies, collective effort from the utilities to standardize will be critical, especially for ABB. In order to facilitate Smart Grid implementation to the power system smoothly, the new standard has to be compatible with existing standards and systems. Furthermore, this new standard has to be implemented throughout different utilities, gradually reducing the variations in different locations.[9] The challenge is whether it is possible to motivate utilities to standardize and transform their existing system.

2.3.4 Smart Grid Features and Communication

Smart Grid can be defined and characterized in many different ways. Depending on the implementations, the focus of the technology can be changed. In the paper [12], the author defined characteristics of Smart Grid that are not available in existing power grids: Digital, two-way communication, sensors throughout, self-monitoring, self-healing, automated billing, power theft detection. These characteristics will enable various implementations, such as Advanced Metering Infrastructure (AMI) and renewable energy integration. It is important to note that most, if not all, of these characteristics have a close relationship with advanced communication. For example, in order to have sensors throughout with self-monitoring and self-healing, there should be complex and interactive communication structures among devices at different levels. The paper [8] provides a good summary of the Smart Grid elements:

- 1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
- 2) Dynamic optimization of grid operations and resources with full cyber-security.
- 3) Deployment and integration of distributed resources and generation, including renewable resources.
- 4) Development and incorporation of demand response, demand side resources, and energy-efficiency resources.
- 5) Deployment of 'smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
- 6) Integration of 'smart' appliances and consumer devices.
- 7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.

- 8) Provision to consumers of timely information and control options.
- 9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
- 10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

Note that these elements are related closely to utilization of large data in power system and advanced two-way, digital communication. Advanced communication technology and infrastructure is the key enabler of Smart Grid features. Furthermore, these features will impact the communication interface of protection and control relay, as it is one of the critical components in the power system.

2.3.5 Motivation for Smart Grid Technology

Smart Grid is slowly coming to the market. Even though there are still ambiguities in definitions, requirements and standards, many drivers are pushing new features into the power industry. The following is the overview of Smart Grid drivers provided in [13]:

1. Attention from government, environmental groups, and customers
2. Increasing electricity demand including electric vehicles
3. Distributed energy source with renewable into the power system
4. Government regulation and funding for Smart Grid implementation
5. Reliability and security concerns with outage costs

Increasing electric devices, including electric vehicles, add burdens to the existing power grid.

Furthermore, renewable energy sources require power systems to adapt complicated structures with advanced communication infrastructure. Along with the market needs and financial benefits of Smart Grid, there are also regulations and government funding for Smart Grid applications that are pushing the implementation forward. In 2009, President Obama announced \$3.4 billion in investment as part of the

American Reinvestment and Recovery Act, to implement a “smarter, stronger, more efficient and reliable electric system.”[13]

2.3.6 Challenges

The idea of Smart Grid is simple and clear. However, the implementation of Smart Grid involves various challenges. Utilities form natural monopolies due to a highly regulated environment, high barriers to entry, high capital requirements and positive economies of scale in production. Thus, these utilities usually lack incentive to implement new innovations. R&D expenditure in the utilities industry is one of the lowest of all major technology-based industries.[8] One of the key aspects of Smart Grid is to prevent outages more effectively by using smarter devices and reliable communication. However, system level implementations of Smart Grid features are costly and it is hard to monetize, except for rough estimations, immediate benefits from many of the applications. Furthermore, it is hard to guarantee improved quality and benefits until a large proportion of the power system is transformed. On the other hand, many utilities in the US have implemented, or plan to implement, advanced metering systems (AMI). Note that one of the reasons for the high penetration of AMI is because it is easy to observe immediate changes and benefits with relatively easy implementation and without interfering with the existing system.

Specifically in communication, there are several barriers to Smart Grid implementation. From the perspective of communications in Smart Grid, the following are the main challenges discussed in [13]:

1. Outdated Communication network
2. An exponential increase in data available in the power system
3. Privacy concerns
 - a. Identity theft
 - b. Tracking customers' personal behavior

c. Real-time surveillance

Communication in current power grids mostly consists of closed network systems where information only flows around internally. Smart Grid implementation will result in more interactive communication among devices and increased availability of information. This also means that the information can be assessable by others who can potentially interrupt the grid system. A statement by Bennie G. Thompson, Chair of the U.S. House Committee on Homeland Security, at the introduction of the “Critical electric Infrastructure Protection Act”, shows increasing concerns about the security of Smart Grid:

“The electric grid is highly dependent on computer-based control systems. These systems are increasingly connected to open networks such as the Internet, exposing them to cyber risks. Any failure of our electric grid, whether intentional or unintentional, would have a significant and potentially devastating impact on our nation.” [13]

Lastly, even though many organizations are developing standards for Smart Grid features and communication, there are various communication technologies and protocols used by the utilities. In order to implement new functionalities effectively, communication standards for different layers of the power systems as well as for layer-to-layer information exchange will be critical. Along with this protocol, various communication technologies need to be evaluated for the new communication infrastructure around the protection and control relay.

3 Communication in Next Generation Product

3.1 Opportunities and Trends

3.1.1 Fiber optics stays as a strong candidate for critical communication

From the traditional analog and binary copper wire communication of electro-mechanical relays providing signal using simple LED, the technology has been evolved to sophisticated microprocessor relays with various serial and Ethernet communication options for protection, control and monitoring features. Compared to copper wires, fiber optics provides reliable, secure and fast communication. Even though there are disadvantages of this technology such as high implementation cost, fiber optics is the most attractive communication option for the power industry. In section 2.2.1, the strengths and weakness of fiber optics has been discussed. As fiber provides more reliable and secure communication with less interference over all other communication technologies, it is very attractive to the power industry to enhance reliability and security of the power grids. Figure 3.1 shows that fiber optics is the most popular technology used for communication links between substations and other locations and utilities are planning to expand their use of it. Figure 3.2 shows the current and forecasted use of communication technology in the power utilities for backhaul and SCADA communication. Note that fiber optics is clearly used by the most utilities for different implementations and expected to grow in the near term. However, even though fiber optics is widely used for communication within and across substations, the survey results also show wide variation of technologies used in the industry. With the implementation of advanced features, distribution feeder relays will be required to enhance communication capability for long distance communication with different IEDs. The ABB medium voltage group should focus on providing fiber optics as the main form of long distance secure communication especially since it is forecasted that fiber optics will be a dominant form of communication for the SCADA system.

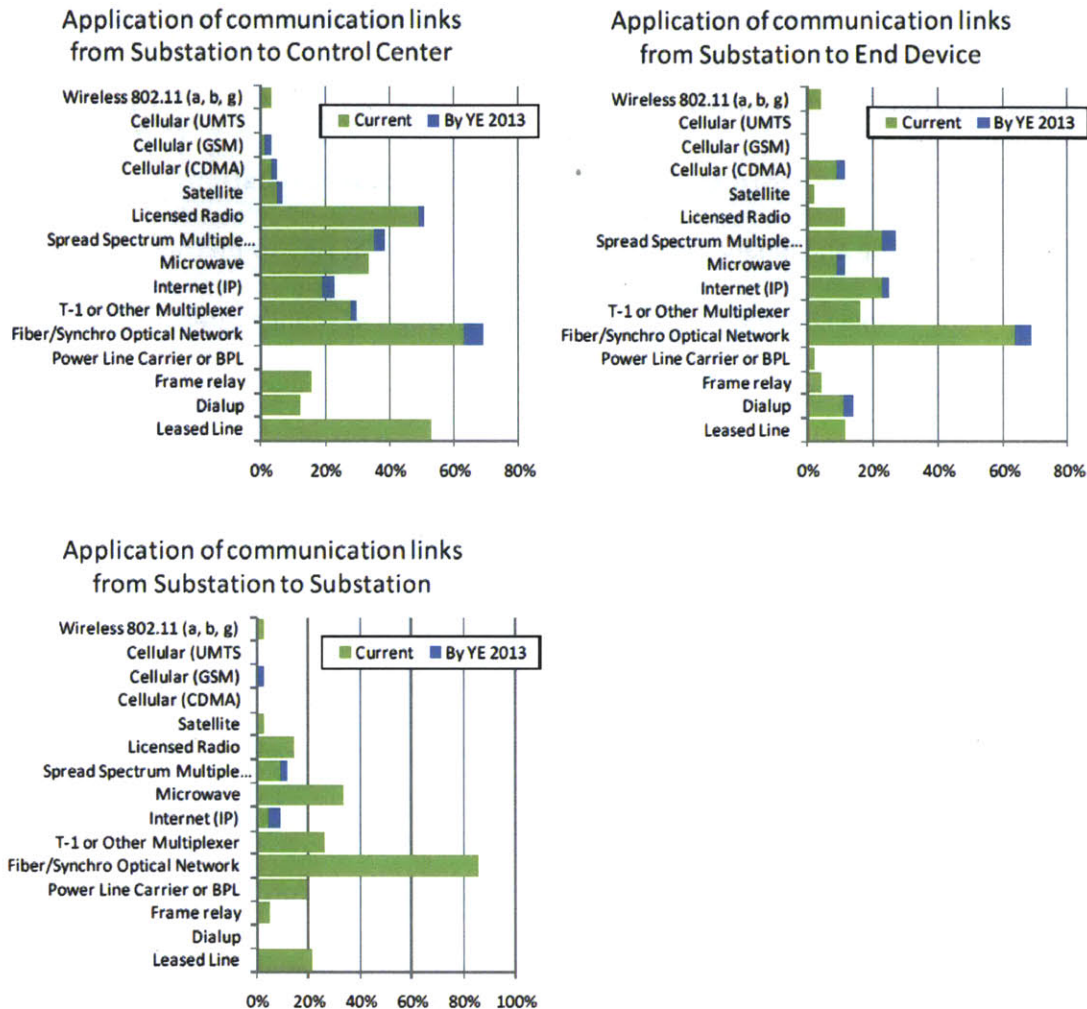
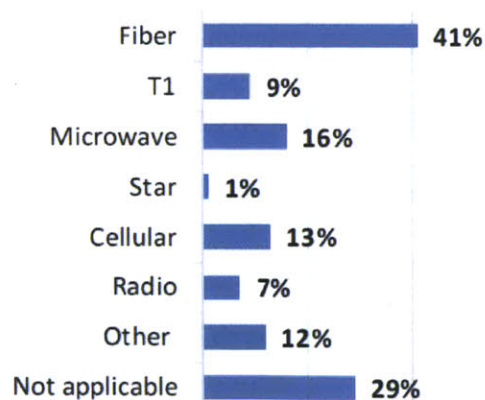
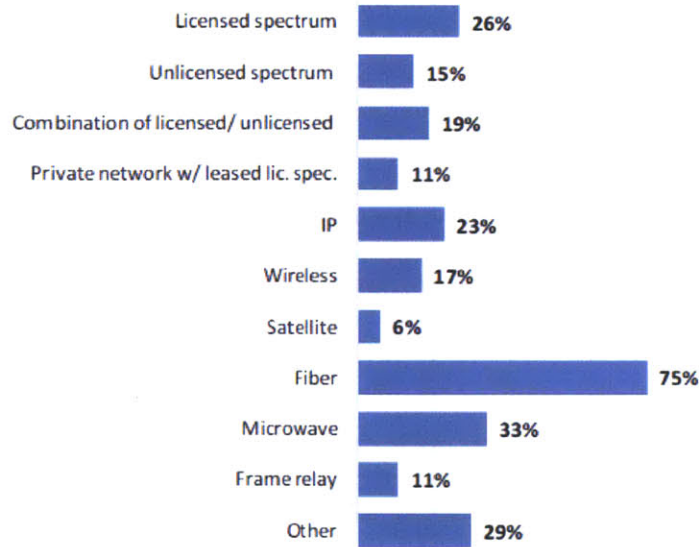


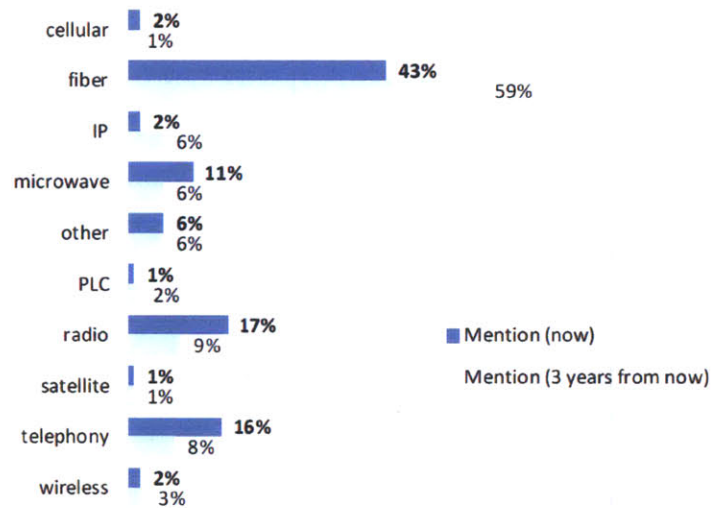
Figure 3.1 Use of fiber optics in different communication links [14]



(a) Communication technology usage for backhaul communication



(b) Communication technology usage for SCADA system



(c) Communication technology expected to be used for SCADA system in the future

Figure 3.2 Use of Fiber optics in (a) backhaul communication, in (b) SCADA system, for (c) future SCADA system [10]

High implementation cost has been the main disadvantage for fiber optics technology, especially considering the scale and complexity of the power grid. However, the price of fiber optic implementation has been dropping rapidly. Despite fiber optics manufacturing being a mature process without large reduction potential in fiber wire prices, other components related to fiber implementations, such as connectors, adaptors, and passive devices are predicted to drop by 90% in

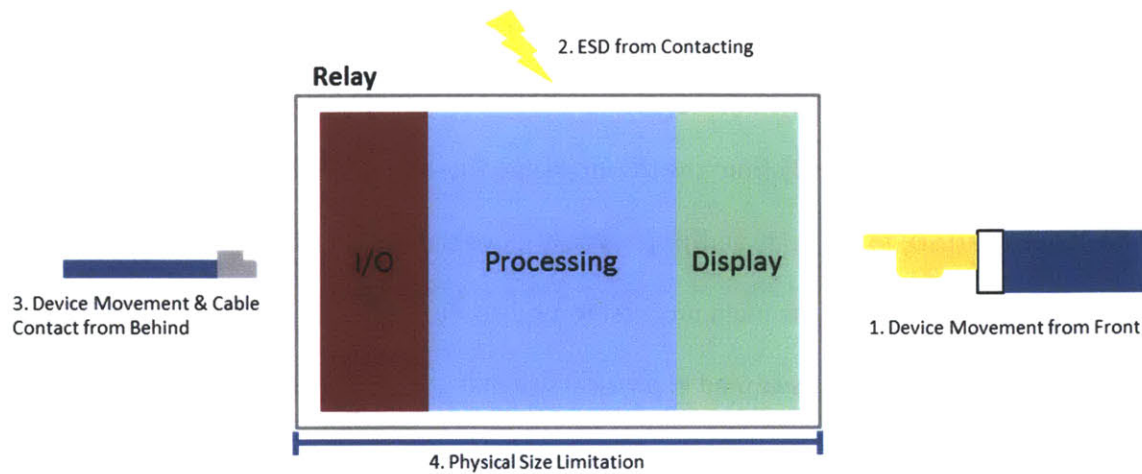
price. [15] This cost decrease in fiber implementation will allow utilities to use this technology more and enjoy its high reliability, security and throughput. Table 3.1 shows comparisons of general wireless technologies and fiber optics. It is clear that wireless technology will reduce wiring and provide better expandability over wired technology. However, in other areas, wired communications, especially fiber optics, provide better throughput, security, reliability, and latency that are desirable for the power industry.

			Ethernet		
	WiFi (802.11)	Fiber Optics	Copper Wire	3G	4G/LTE
Type	Wireless	Fiber Cable	Land Line	Wireless	Wireless
Ownership	Private	Private	Private	Public	Public
Throughput (Data Rate, in kbps)	11000 - 150000	> 1G	10000-100000	384-2000	100000 (Down) 50000 (Up)
Coverage	75 - 150 m	Far	< 100 m (indoor)	1 - 10 km	1 - 10 km
Spectrum Availability	2.4 GHz (G, B)	-	-	1.92-1.98 GHz	Multiple
	5 GHz (N)	-	-	2.11-2.17 GHz	
Cost	Low-Medium	High	Medium	Medium	Medium-High
Security	Medium	High	High	Medium	Medium-High
Reliability	Medium-High	High	High	Medium	Medium-High
Life Cycle	Mature	Mature	Mature	Mature	Emerging
Technology Risk	Low	Low	Low	Low-Medium	Medium
Latency	Medium	Low	Low-Medium	Medium	Medium

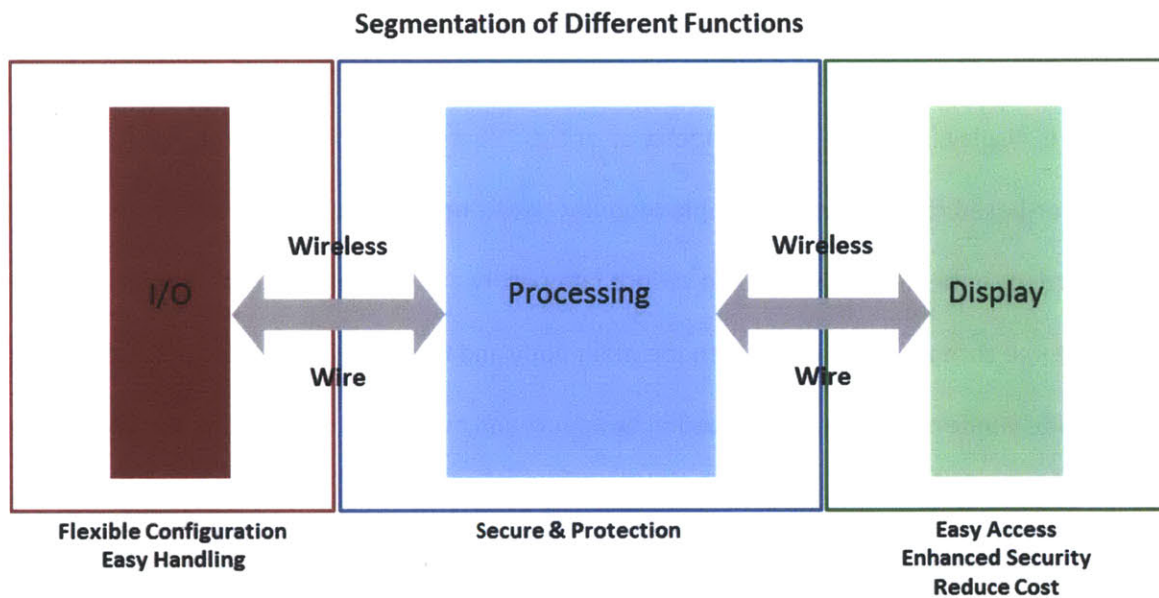
Table 3.1 Comparison of fiber optics and other wire/wireless technologies (Appendix A)

3.1.2 Segmentation of Internal Functions

Protection and control relays started as an electro-mechanical device where a user can see a rotating disk and LED light if event occurs. In the era of microprocessor-based relays, hundreds of functions and features related to protection, control and monitoring have been added to the device with an increasing number of I/Os and communications capabilities. Figure 3.3(a) shows the current microprocessor relay with different functions. It also shows potential issues that can rise from the current design.



(a) Current Relay Structure and Issues



(b) Segmentation of Different Functions and Potential Benefits

Figure 3.3 Segmentation of Relay by Function and Potential Opportunities

The protection relay can be divided up into three different parts: I/O interface at the back of the relay, front panel for human interface and main processing module. The I/O interface provides connections to the inputs and outputs including analog and digital communications. The front panel is located at the front of the device and the users can access settings and information. The main processing unit consists of various electronic components such as CPU, FPGA and RAM, runs protection and control features,

and makes decisions. There are several issues related to the current design. The user can interact with the relay using the front panel display to configure the setting and acquire data. The user can also make physical contact with the relay directly from the I/O interface. These actions can potentially create electrostatic discharge (ESD) to the relay and/or physically move the device, which are undesirable for sensitive electronic components in the main processing module. Furthermore, the relay box, where all the components are tightly packed, is limited in physical size that can raise thermal issue and decrease the flexibility of the relay. In order to address these issues, segmentation of the relay by different functions is required. By segmenting the I/O interface, main processing module and front panel from each other as shown in Fig. 3.3 (b), there will be multiple benefits.

The front panel display is not the core competency of the ABB medium voltage group. As microprocessor-based relays contain multiple modules tightly packed into the box, the front panel can easily add burden to the device. In order to reduce complexity and increase flexibility, it is more optimal to standardize the communication between the main body and front display, and to outsource the front panel to outside vendors who are specialized in designing and manufacturing the display. This can also provide flexibility to the location of the main processing body and protect sensitive and critical components from direct physical contacts. Furthermore, multiple devices can be controlled using only one panel, which can reduce the cost of the relay. With enough security features, wireless technologies can be used for the interface between the main body and the front panel, which will further improve the user experience.

The main processing module is the core competency of the ABB medium voltage product group. This group is responsible for creating hardware architecture, generating specifications protection and control features and implementing into the main processing module. Thus, the team has tremendous expertise in this module. By segmentation along the different functions, the team can focus heavily on its core

expertise with more flexibility for improvements. For example, by detaching front panels and I/O interface, main processing modules can be stored in a secure deck with enhanced ventilation and prevention from physical contacts.

Lastly, input and output interfaces provide various communication channels between the relay and other devices. The I/O interface is a critical component for the relay, but it is another component that limits the flexibility of the device. By segmentation of the I/O interface from the main processing module, ABB can more easily meet the various needs of utilities that have different communication standards and technologies. However, as this interface is closely related to the core functions of the device and any failure is highly risky, it will be difficult to separate the two different areas in the near future, but such an option should be further studied for future relay products.

3.1.3 Wireless will be used for user experience related applications

Even though the security and reliability of wireless technology has evolved rapidly, concerns and doubts still exist. Since utilities pay for high outage rates, the communication system for protection and control has to be highly robust and secure. This creates a conservative industry that is distinct from other consumer electronics markets. As a similar example, hardware components used for space exploration cannot tolerate failures, as replacement is impossible, requiring a high level of robustness and tests. In this stringent case, reliability of the devices has higher priorities than performance. The fundamental question is whether wireless can provide enough capability in those areas to be used in power systems, and the answer can be yes in some situations. However, there are also arguments about the risk of wireless security and reliability. Regardless of whether wireless technology can provide enough security for the power system or not, the perception of decreased reliability exists, and those doubts and concerns hinder the utilities from implementing innovative and new ideas using wireless technologies in high-risk areas. Advanced functionalities, such as distributed energy sources and improved reliability and

security of the power system, are attempts to improve the power system and reduce outage costs while providing more monitoring and control features. Distribution feeder relays will play one of the major roles in applying these new functionalities that require highly reliable and secure communication. Thus, utilities will hesitate to implement wireless technologies as a main form of communication in risky areas as they have fiber optics as a strong candidate.

The protection and control related applications require high level of security and reliability. However, there are other non-critical applications, such as PC and front panel to relay communications and asset health applications, where communication requirements can be relaxed, as they don't impact the protection system directly. For these monitoring and user experience related features, wireless can definitely enhance the system efficiency and provide competitive strengths to power electronics companies in the market. On the following subsections, potential wireless implementations and communication opportunities for the protection and control relay that can aid user experience will be discussed.

3.1.3.1 Bluetooth and other near field communication

Bluetooth and other near field wireless technologies can be used to enhance the user experience in many different ways. Wireless technology in general is still questionable to be used in specific channels with high security and reliability requirements. However, for less-critical channels, these technologies can provide operators with remote access to the device. Bluetooth is used widely for low-power, close-distance and portable device applications. Furthermore, Bluetooth is relatively easy to use and set up and thus can be used by most individuals with the proper device and authentication.

With proper identification and security features, there are many opportunities for Bluetooth to be applied for various purposes. In the previous section, a possibility of implementing a detachable display has been discussed. For the communication of one display to one or more relays, Bluetooth technology

can be used also. Furthermore, for the relay-to-PC interface, most devices only support direct wire connection to the relay for accessing the information. This can be disturbing for the operators if the device is hard to reach physically. Schweitzer Engineering Laboratories (SEL) recently announced an external Bluetooth device that can be attached to the relay or other device serially, providing remote access to operators. Figure 3.4 shows the Bluetooth external device by SEL.



Figure 3.4 SEL 2925 Bluetooth Serial Adapter, SEL website

3.1.3.2 Developed vs. Emerging Market

Developed countries like the US have a well-structured and well-organized power infrastructure. Furthermore, standards and communication technologies are mature compared to emerging markets. For many decades, power lines, generation, transmission, and distribution of electricity have been developed and evolved to provide electricity to almost every household without difficulty. On the communication side, customers are familiar with many of the technologies, such as land line, cellular, Wi-Fi and so on. The utilities already have systems and networks used for SCADA and other features. The major challenge for the developed countries is to effectively and cheaply transform and replace the existing power system to adapt to the complex and sophisticated Smart Grid.

On the other hand, developing countries operate under very different environments. Power systems in those countries are newly built and have the potential for advanced features to be implemented directly

from the beginning. Furthermore, their communication systems may be immature and landline coverage could be limited, which creates larger opportunities for wireless communication. For example, in sub-Saharan Africa, there are fewer than three landlines available per 100 people, but ten times as many mobile phones are available than landlines in 2009. Furthermore, 60% of the population has mobile phone coverage.[16] This shows that wired communication infrastructure is relatively weak in emerging market and wireless communication, such as cellular, is rapidly penetrating these markets. For utilities in these emerging markets, wireless solutions can be attractive over wired technologies in new substations where infrastructure is not yet mature.

3.1.4 External Implementations for Smart Grid will continue

Ideally, utility companies will desire to employ a single device that has all protection and control features and communication capabilities. However, due to hardware restrictions and the existing power infrastructure, it will take significant time to meet all communication needs using one single device. Currently, with the ambiguous definition of new functionalities and varieties in technology implementations, it is impossible for a supplier to meet every single scenario of the customers' needs. Thus, rather than trying to implement specific communication technology into the product, it is optimal to provide external supports that can meet various communication needs. This means that the product, both in hardware processing capability and communication interface configuration, has to be flexible to adapt to different options. Communication interfaces can be converted and handled by external devices, but the relay needs to run data processing and major features to support advanced functionalities.

Most, if not all, of current wireless implementations in the relay has been done using external wireless router connected to the relay through Ethernet or serial port. This is a simple and flexible way of accommodating various wireless technologies without changing the relay itself. However, there are several issues related to external implementations. First, current external wireless devices are

expensive; an individual router can easily cost several thousands of dollars. Thus, external devices can be a short-term remedy for small scale and pilot program implementation, but electrical equipment companies need to eventually develop an integrated communication solution that can provide flexible options to the utilities. Another issue arises from the ownership and control of multiple devices. With an increasing number of devices from different stakeholders, maintenance and control becomes trickier and complicated. Any failure or breakage on the chain of devices is harder to detect and trace compared to a single device with self-monitoring and reporting features. For critical communication lines, multiple ownerships and complicated interfaces can create reliability weak-points and difficulties in tracking responsibility of any failure. In order to mitigate this complexity, the ABB medium voltage group should work closely and cooperatively with network providers in implementation of external wireless technologies. The recent acquisition of Tropos Networks will enable the ABB medium voltage group to extend wireless communication capability where the group can develop, manufacture and service both distribution automation devices and wireless solutions to utilities. The medium voltage group should maintain close cooperation with the team and further enhance the capability to provide external options for the utilities.

3.2 Challenges in Implementation of New Relay Communication

3.2.1 ABB Power Products Medium Voltage

The power products groups in ABB are facing environmental changes in the industry. With Smart Grid slowly impacting the traditional power grids, the utilities are implementing a wide variety of functions such as distributed energy sources and enhanced monitoring and control capabilities, using different technologies and this divergence will keep increasing. The power products groups in ABB invest and search for technical innovations for next generation products, but it is difficult for them to radically change existing products due to various reasons discussed in the following subsections. Although the

protection and control relay is one of the key elements to increase protection and control of the power system, Smart Grid implementations will most likely focus elsewhere initially, such as the upper level information system or peripheral areas. This means that when transformation of protection and control relay communication happens, the utilities may already have wireless technologies and communication systems implemented in their power system. Furthermore, there is no industry standard and each utility can simply pick and choose what they want to implement. The various legacy technologies in the utilities will cause difficulties in meeting the needs of utilities as far as interoperability among old and new devices. Further discussions on these challenges are provided below.

i. Interoperability with older devices

Old substations have various versions of legacy and new products already implemented using certain infrastructure and protocols. Thus, in order to implement new infrastructure with advance communication capabilities and new standards, it is ideal to build new substations and entire systems. However, the cost of building new substations is extremely high. Furthermore, the new substations will replace old ones, which are currently serving multiple customers and their service must not be interrupted. Thus, a significant portion of distribution and automation device sales rely on replacement of older devices within existing substations without interrupting the company's services. The life cycle of microprocessor-based relays is around 10-15 years, which means that there could be many versions of products implemented in different locations. These older devices have certain interfaces to communicate with other devices in the substations. Utility companies expect to replace their old devices by simply swapping without changing the interfaces and impacting service. However, this introduces another layer of complexity for the ABB power product group and limits innovation and opportunity for changes. While adding more features, functions, and capability to the device, the communication interface has to stay relatively unchanged and support various options including both new and old systems. Furthermore, new devices might operate in the environment where surrounding devices are

legacy products with limited communication flexibility. Interoperability of the next generation protection relay is a critical and important aspect of a seamless transition from the old system to the new Smart Grid infrastructure; this will require increased complexity in communication and hardware options for the devices. Interoperability will be one of the major concerns and limitation for implementing advanced communication to next generation relay products. One of the potential solutions to mitigating the increasing complexity and to stay flexible is the segmentation of the present feeder distribution relay as proposed in section 3.1.2. By separating the I/O interface from the main processing module, it is possible to use the same interface after the main processing module is changed, whenever necessary. Furthermore, it is also possible to convert the communication interface without replacing the main processing module. This will enable the utilities to modularly convert their substations without interrupting the entire system. For ABB, the company will be able to react faster to the market changes as segmentation of the relay provides flexibility in design and a facile method for modular changes.

ii. Product Level Challenge

The present protection and control relay consists of many communication interfaces including analog, binary and digital. For digital communication, serial and Ethernet communication using copper wire or fiber optics is common. Even though the number of options is small, there still exist different combinations of the technologies creating a huge number of communication card options for the customers. For example, for the ABB Relion relay family, there are tens of combinations of communication technologies and protocols that customers can choose with various standards. Additional communication technologies and protocols will increase the number of options exponentially resulting in increased cost and difficulties in supporting all the options. If wireless is used for various Smart Grid implementations, the number of options for this implementation will also increase the manufacturing cost further and can introduce hardware implementation challenges. Note that it is

difficult for the ABB medium voltage group to limit the options of communication technology or protocols as they are heavily driven by the need of utilities themselves. Utilities run separately from each other and electrical equipment companies have traditionally lacked the power in NA to push technology to the utilities. Different utilities have freedom to choose their infrastructure and communication technologies that fit their needs best. Fortunately, the protection relay rarely communicates directly to the higher level of the system, so communication variations should have less impact at the system level. Until the definition of Smart Grid becomes clear and standardized, electrical equipment companies should rely on external communication implementation for the need of utilities while actively participating in the development of industry standards. Even though the standards are vague at this point, efforts to define uniform protocols for Smart Grid infrastructure will eventually provide more efficient technology for the industry. ABB should actively involve in the standards committees to understand and promptly react to the evolving industry.

3.2.2 Reliability and Security

According to the document from the US Department of Energy, “Today’s electricity system is 99.97 percent reliable, yet still allows for power outages and interruptions that cost Americans at least \$150 billion each year – about \$500 for every man, woman and child” [17], which highlights the high cost of failure in the power grid. Reliability and security are the most important parameters for protection and control device as outage is extremely costly. Reliability for wired communication may be the probability of wire theft and disconnects caused by physical incidents such as a tree falling. While wireless technologies don’t have to worry about the above problems, they introduce different categories of reliability problems that depend on traffic and signal strength. Any communication change has to provide sufficient evidence that the reliability of wireless will either stay the same or be improved compared to wired control.

Another important aspect is security of accessing the system and information. The system, including communication, has to be robust enough to prevent any unauthorized effort to break through the system. Security in wired communication means physically tapping onto the wire, accessing information and interrupting the system. Thus, authentication and encryption in the communication layer will be critical to enhance the security. For wireless communication, information is contained in certain frequencies in the air, which can be accessed without any physical connection. Thus, additional security features, such as frequency hopping, are necessary to guarantee high security for critical communication channels. These features of wireless technologies increase security of the system, but still can't provide level of security as high as fiber optics or copper wire. Changing communication interfaces, for both wired and wireless, includes risks and concerns that hinder utilities from actively adopting new technologies. However, it is true that with careful analysis, the utilities, including ABB, can identify critical channels that require high reliability and non-critical ones with relaxed specifications. By identifying critical and non-critical channels, it is certainly possible to improve communication efficiency with low risk. From the current distribution feeder relay analysis in section 2.1, the communication channels can be divided depending on the different reliability and security levels. Table 3.2 shows the security and reliability requirements at each level for distribution feeder relay communications.

Point A	Point B	Security	Reliability	Integrity	Latency
Instrument Transformer	Relay	High	High	High	Low
Arc Detection	Relay	High	High	-	Low
Relay Binary Input	Relay	High	High	High	Low
Concentrator	Relay	High	High	Medium	Low
Relay Binary Output	Relay	High	High	-	Low
Relay	Relay	High	High	Medium-High	Low
SCADA	Relay	High	Medium	High	Medium
Front Panel	Relay	High	Medium	Low-Medium	High
Sensor	Relay	Medium	Medium	Medium-High	Medium
PC	Relay	Medium	Medium	Medium	High

Table 3.2 Security and Reliability of Relay Communication Channels

The channels requiring high level of security and reliability are mostly related to protection and control features, whereas the lower level ones are related to data acquisition and monitoring features. For those channels requiring high security and reliability, which will be difficult to change from the current wired communications, fiber optics has clear advantages over copper wire in reliability and security. For communication channels related to monitoring and data acquisition, although the protection from the unauthorized access is necessary, these channels are less related to failure in the power line. Thus, ABB will have room to implement different communication technologies for these channels, such as the wireless access, as seen in section 3.1.3.

3.2.3 Cost

Cost is another important aspect of the distribution feeder relay. Compared to high voltage products, medium and low voltage products are located closer to the consumers, bearing less risk and incurring less expense from a power outage. Thus, distribution feeder relays are priced lower than transmission and transformer relays because of their limited hardware and communication capabilities. However, as discussed briefly in section 2.1.3, there are different communication standards for protection relays depending on the options. Combined with various possible combinations of protection and control functions, the utilities may need to provide tens of options for a single product. Therefore, even for the medium and low voltage products, different communication card options in a relay impact the size of the relay itself. The variation in product configuration creates increased manufacturing cost and further complicates the R&D process. In this situation, wireless could be incorporated in the design of the relay to reduce the cost and improve the efficiency of the system. As more and more advanced functions are required for distributed energy sources, asset health, and monitoring, it is necessary to introduce new standards and communication technologies into the relay and increase the number of configurations for functions and communication technologies.

In order to mitigate the increasing complexity and lower the cost of the distribution feeder relay, segmentation should be considered seriously as shown in section 3.1.2. Segmentation of the current feeder relay suggests dividing the product into the I/O, the main processing module and the front panel. For example, by removing the front panel, for which the ABB medium voltage group does not have expertise, for example, it is possible to remove any failure or issues related to the front panel while reducing the unit cost of the relay. The external front panel can be manufactured cheaply by third parties that have expertise and also multiple relays can be used with one front panel design to reduce total cost. The main processing module of the relay, consisted of the CPU, FPGA and other electronic components, runs for protection, control and monitoring functions. The capability of the main processing unit is similar for all utilities and functions and features can be added simply to the system as long as the hardware performance allows. The I/O interface creates a wide variation for each implementation. Thus, by segregating the main processing module and the I/O interface, ABB can provide flexible options in I/O while keeping the main processing module same. This will make the upgrades in communication interface or hardware capability simple and cheap, as the utilities do not have to change the entire device.

3.3 Strategy for ABB

3.3.1 Collaboration of different products and power groups

Interdisciplinary application is essential these days in every industry to meet the diverse and increasing needs, which inevitably results in technologies used in unexpected ways. Applications in the power grid are not an exception to this trend to include advanced functions, to increase the efficiency of the system management, and to enhance the reliability of the power grid. In order to serve different needs of utilities, the ABB Power Product division is currently organized along different power levels and their related products: High and Medium Voltage Group and Transformers Group. In the past, there has not been much overlap on product development among those different divisions as most of R&D activities

are related to specific hardware and functional requirements of their own divisions. In addition, there was no necessity for complicated communication exchange among devices since they performed simple tasks and functioned nearly independently. This structure has worked fine before more complicated and advanced functionalities were added to the system, together with the rapid increase of information exchange among devices. Now it became absolutely indispensable for various teams to work closely together from the very beginning and share information to develop next generation products. It is not only to develop the new products, but also to manage the whole system efficiently and to meet the various requests of customers without delay. New ideas in the power grid business, such as implementing advanced features or adopting wireless communication, should be tested and applied actively to create new business in the future.

For ABB, the first step toward this direction could be a reorganization of the business structure. Smart Grid is trying to improve its efficiency and reliability through an advanced communication infrastructure. For the next generation distribution feeder relay having advanced protection, control and monitoring features, there should be cooperative efforts in R&D activities as well as good information sharing among different teams. However, ABB US does not have a good cross-functional system yet. For example, to implement asset health features in existing devices, data from various sensors should be processed in the Central Processing Unit (CPU) which is available in the relay or the concentrator and the team responsible for asset health needs to work together with both other teams developing the relay and the concentrator. In the present structure, however, because of the geographical and organizational constraints, the current ABB US offices are limited in their cooperative activities, and in implementing and developing new ideas.

The main reason that collaboration among different groups and teams in ABB US is challenging is the geographical separation of the offices. As they are located in different regions from one another, there

is a tendency to keep information within the group and refuse to share with other teams. Such a silo effect can impede the development of new and innovative technology for the next generation product. The power grid will evolve differently from nation to nation, region to region, since each country or region has distinctive characteristics in legislation, geography, and culture. Thus, ABB should develop its regional R&D capability with the efficiently focused structure for market-specific products to actively and rapidly cope with evolving industry.

3.3.2 Practical Technical Suggestions

One way to solve the technical difficulties in meeting various needs could be creating more flexible platforms where hardware, software and communication capabilities can be configured or upgraded easily. This effort should be made as a cooperative work among separated groups rather than by a single group, which also can be an opportunity to improve communication and to share information among groups. Firstly, reassess the technical requirements of the product in light of the projection of the future power grid in the US, decide basic common features collaboratively, make room to apply new ideas, such as wireless communication among devices, and make a standard platform for the product suitable for the regional market. The business structure in US should be reorganized along the main group, which deals with the standard platforms, and subgroups, which develop additional functions for, specialized features. All information and communication should flow through the platform group, which will significantly improve the efficiency of management.

The ABB medium voltage power product group should be a future core technology group developing the standard platform for high-end distribution feeder relays, which have enhanced hardware and communication capabilities, and also for low-end products that support the current infrastructure which can be a replacement for old devices. The next generation relay might not be able to include all Smart Grid features and communication requirements. Thus, it is important to find alternative solutions for the

users who desire to simply replace old devices. Rather than creating a single product having different configuration options, developing a separate product for each application, e.g., high-end Smart Grid application and low-end non-Smart Grid application, could be an answer to meet the various customers' needs. The ABB medium voltage power product group should be prepared for the next generation power grid. Only with continuous reformation of the business system and continuous development of the new technology devices, can it survive in the market and meet the needs of customers successfully.

4. Conclusion

4.1 Summary

This thesis starts with understanding the evolution of Smart Grid applications and communication technologies. The definition of Smart Grid, along with standards and requirements, is currently diverse and uncertain in many respects. Furthermore, due to the conservative nature of the utility industry, the degree of Smart Grid penetration will vary among different regions and countries. To the power electronic suppliers, this means that the next generation products will require a wider range of hardware, software and communication specification depending on the required applications and customer needs. Moreover, it is critical that new products interoperate with older devices and systems, which add another layer of complexity. This thesis addresses the potential communication evolution for Smart Grid implementations, especially focusing on the protection and control relay aspect. For protection and control features, wireless technology will not be the dominant technology in the near future, since fiber optics proves to be more effective, secure and reliable. As for the need of certain utilities, external implementations of wireless technologies will be made with the collaboration of wireless providers. Note that this does not mean wireless will never penetrate the market successfully; for example, for emerging markets where communication infrastructures are not well-defined, wireless technologies can play a major role. Further studies, such as comprehensive business case analyses, should be performed before implementing new technology and transforming devices for the Smart Grid. We must understand how Smart Grid is evolving from both market and technological perspectives. The winner of the next generation distribution feeder relay will not only satisfy the customer needs and market requirements but also deliver new and innovative solutions to enhance the reliability and efficiency of the power grid.

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Appendix A. Wired & Wireless Technology Overview

					Ethernet					PLC			
	WiFi (802.11)	ZigBee	Bluetooth	Fiber Optics	Copper Wire	2G	3G	4G/LTE	WiMax	Narrowband	Broadband	Satellite	Leased Line ¹⁾
Type	Wireless	Wireless	Wireless	Fiber Cable	Land Line	Wireless	Wireless	Wireless	Wireless	Power Line	Power Line	Wireless	Land Line
Ownership	Private	Private	Private	Private	Private	Public	Public	Public	Private/P ublic	Private	Private	Public	Public
Throughput (Data Rate, in kbps)	11000 - 600000	20-250	721	> 1G	10000- 100000	14.4	384-2000	100000 (Down) 50000 (Up)	75000	upto 500	1000	56	1500
Coverage*	75 - 150 m	30 - 50 m	1 - 100 m	Far	< 100 m (indoor)	1 - 10 km	1 - 10 km	1 - 10 km	10 - 50 km (LOS) 1 - 5 km (NLOS)	-	-	Wide	Far
Spectrum Availability	2.4 GHz (G, B) 5 GHz (N)	2.4 GHz 868-915 MHz	2400-2480 MHz	- -	- -	900-1800 MHz	1.92-1.98 GHz 2.11-2.17 GHz	Multiple	2.5, 3.5, 5.8 GHz	- -	- -	Multiple	- -
Cost	Low- Medium	Low	Low	High	Medium ²⁾	Medium ³⁾	Medium ³⁾	Medium- High ³⁾	Medium	Low-Medium	High	High	Medium- High ³⁾
Security**	Medium	Medium ⁴⁾	Low- Medium ⁵⁾	High	High	Medium	Medium	Medium-High	Medium- High	Medium	Medium	Medium	Medium-High
Reliability	Medium- High	Medium- High	Medium	High	High	Medium	Medium	Medium-High	Medium- High ⁶⁾	Medium	Medium	Medium	Medium-High
Life Cycle	Mature	Emerging	Mature	Mature	Mature	Mature	Mature	Emerging	Mature	Mature	Emerging	Mature	Mature
Technology Risk	Low	Medium	Low	Low	Low	Low	Low- Medium	Medium	Low- Medium	Low	High	Medium	Low
Latency	Medium	Low- Medium	Medium	Low	Low- Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Low-Medium

¹ Leased line provides guaranteed communication by third vendor. Customer does not care how leased line company connects internally

² Copper wire cost depends on the distance coverage

³ Monthly Fee applied but no infrastructure Cost (reduced upfront cost)

⁴ 128 AES + Application layer security

⁵ 64 & 128 bit encryption

⁶ WiMax can be considered as upscale WiFi that operates using towers. Thus, depending on the number/distance of towers the reliability can vary. Also, WiMax is suited for stationary communication whereas 4G/LTE are better for mobile communication

* Coverage
Coverage can vary depending on many factors such as interference and obstacles. Also, the distance and throughput have inversely proportional relationship. When considering the technology, detailed coverage and throughput requirement have to be evaluated

** Security
Security depends of whether using public medium

Appendix B. Relay Communication Interface Overview

Point A	Point B	Connection	Input Type	Distance ¹⁾	Type of Connection		Throughput	Security	Reliability	Integrity	Latency	Real Time
					Direction	Connection Type						
Instrument Transformer*	Relay	Copper Wire	Analog Current/Voltage	4-1000 ft ²⁾	Unidirectional	Continuous	200K - 1.5 Mbps ³⁾	High	High	High	Low	High
Arc Detection	Relay	Fiber Optics	Light	6 - 12 ft.	Unidirectional	Event-Based	> 1 Gbps	High	High	-	Low	High
Relay Binary Input	Relay	Copper Wire	24-250 VDC	4-1000 ft ²⁾	Unidirectional	Event-Based	Low (<1 Kbps)	High	High	High	Low	High
PC ⁴⁾	Relay	Ethernet/Serial	Digital	6 - 12 ft.	Bidirectional	Event-Based	200-500 Kbps ⁸⁾	Medium	Medium	Medium	High	Low
Concentrator	Relay	Ethernet/Serial	Digital	6 - 200 ft. (Within Substation)	Bidirectional	Event-Based	200-400 Kbps	High	High	Medium	Low	High
		Fiber Optics		1 - 25 miles (Multi location)								
Relay Binary Output ⁵⁾	Relay	Copper Wire	125 VDC / 120-240 VAC	4-1000 ft ²⁾	Unidirectional	Event-Based	Low (<1 Kbps)	High	High	-	Low	High
Relay	Relay	Ethernet	Digital (GOOSE)	6-200 ft.	Bidirectional	Event-Based	30 Kbps	High	High	Medium-High	Low	High
Sensor ⁶⁾	Relay	Various	Analog/Digital	4-1000 ft ²⁾	Bi/Unidirectional	Event-Based/Continuous	Vary ⁹⁾	Medium	Medium	Medium-High	Medium	Low
SCADA	Relay	External Wireless	Digital	6 - 200 ft. (Within Substation)	Bidirectional	Event-Based	200-400 Kbps	High	Medium	High	Medium	Medium
				Far (> 100 miles)								
Front Panel ⁷⁾	Relay	Cable/Ethernet	Digital	0 - 10 ft.	Bidirectional	Event-Based	Low (<1 Kbps)	High	Medium	Low-Medium	High	Low

Note

- 1) Distance (and also for other categories) is not setting technical limitation to implementation, but providing general guideline and observation
 - 2) Distance varies depending on individual implementation. See note below
 - 3) Calculation done using current sampling rate. See note below
 - 4) PC refers to direct connect to relay for firmware update or data acquisition. Distance will be practical distance that operator uses to connect to the device.
 - 5) Binary output from relay. Requirement can be same as relay boundary input. Example connections are circuit breaker, SCADA, adjacent IEDs, and alarm boards
 - 6) Sensors that can be potentially added to the system (for asset health or monitoring). Location of the sensor is close to the devices (e.g. transformers) and distance will be similar.
 - 7) From CPU to front panel communication. REF630 Series provide detachable front panel that can extend upto 10 fts. Currently, one panel per each relay.
For simple firmware update or data acquisition that are currently done using direct connect to the relay, hundreds of bps can be sufficient. However, faster communication means
 - 8) less waiting time for operators.
 - 9) Depending on whether sensor sends raw or processed data, the throughput requirement can vary significantly.
- Instrument transformer refers to the device sending information using analog signals. Recent/future device might have capability to send data using Ethernet cable under IEC61850 standards

Note Details

- 2) Copper wire coverage distance is impacted by various factors
- Copper Wire
Type

Depending on conductor size and material, resistance of the wire changes and thus degradation of voltage level

American Wire Gate (AWG) provides different standards for copper wire (#6, 10, 12) - #10 copper wire used most often and can go upto 600 ft.

Voltage/Curre
nt input

For voltage, coverage distance is impacted by allowable voltage degradation. Thus, lower initial voltage will allow shorter distance.

For current, #10 wire carries 30A

Note: Ideally, actual implemented distance is desirable. However, it is impossible to collect all distance between instrument transformers to relay. Thus, technical limitation used as reference.

Note: By using different technique and wire, the distance can be extended

Calculation for Instrument Transformer to

32	256	Samples per cycle per channel
60	60	Cycles per sec
24	24	Bits per sample
4	4	Channels connected together
184320	1474560	Bits per sec